A Plasma-Based Brightness Transformer

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HELMHOLTZ

DESY.

High Brightness Bunches: Definition and Uses

Brightness

- Density of bunch in 6D phase space
- Low emittance ε_n is critical for high brightness

$$B = \frac{Q}{\epsilon_x \epsilon_y \epsilon_z} \propto \frac{I}{\sigma_E \epsilon_x \epsilon_y}$$

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi \sigma_x \sigma_y}$$

Bright Electron Bunches for Compact XFELs

- Requirement for lasing: energy spread $\sigma_E <$ Pierce parameter ρ (~ 10^{-3}) [1].
- Saturation power ∝ beam power (∝ I).
- Can radiate coherently at shorter λ by shortening the undulator period λ_u.
- Reduced gain length & total FEL length [2].
- An ultralow-ε_n plasma accelerator can drive a compact, cheaper FEL.

$$\rho \propto \left(\frac{I}{{\sigma_x}^2}\right)^{1/3}$$

$$\epsilon_n/\gamma < \lambda/4\pi$$

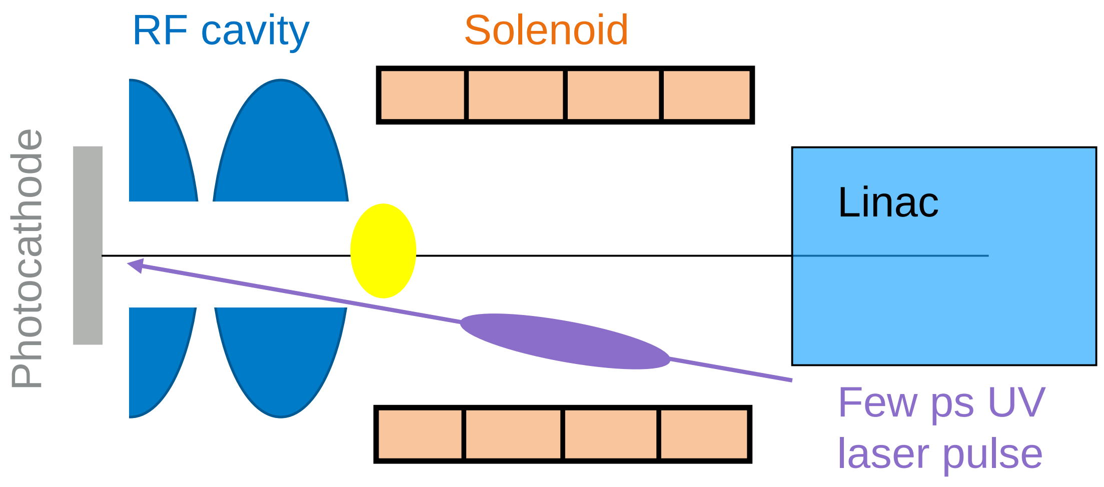
$$L_{G0} = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

[1] Prat et al., Nat. Photon., 2020, https://doi.org/10.1038/s41566-020-00712-8.
[2] Z. Huang & K.-J. Kim, PRAB, 2007, 10.1103/PhysRevSTAB.10.034801

Limitations of RF Guns

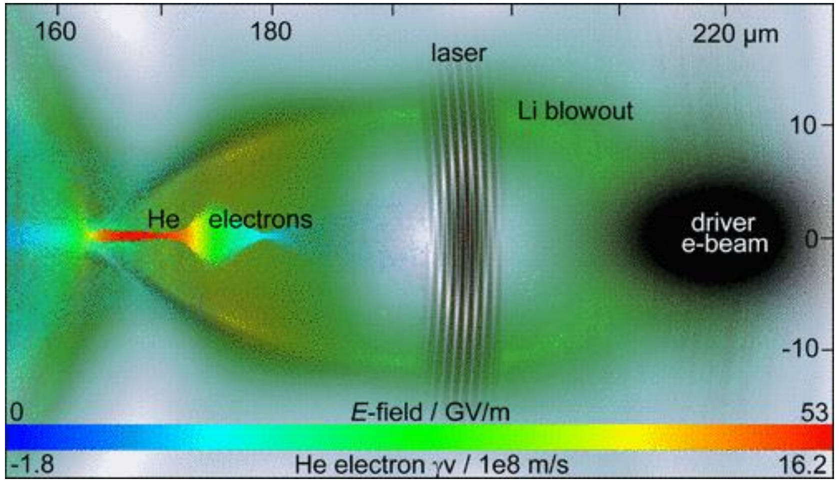
Emittance from RF guns

- RF guns have an intrinsic emittance:
  - Due to laser spot size.
  - Inversely proportional to the quantum efficiency.
- Trade-off beween high charge and low ε_n
- e^- bunches then rapidly expand due to their space charge force until they reach relativistic energies, risking ε_n growth.
  - e.g. FLASH has max 1 nC at 1 mm-mrad from ~ 1 mm spot size.
- Plasmas can potentially improve on this:
  - Natural radial focussing.
  - High accelerating field.
  - Small intrinsic size (need low $p_\perp$ too)

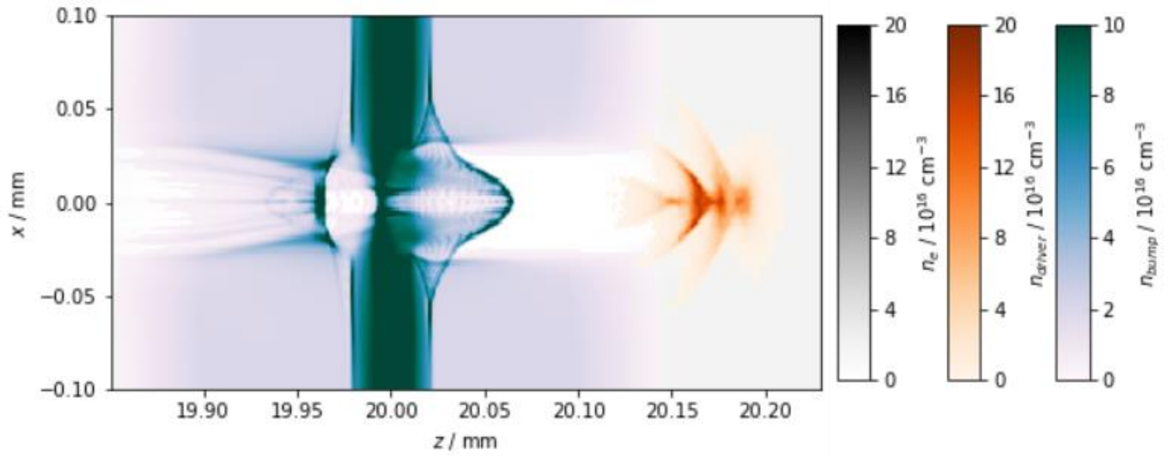


Plasma-Based Injectors

- Unipolar driver field-generates a strong wake without driver-induced-ionisation: plasma shaping for low-emittance injection.
- Two schemes:
  - Trojan Horse: 10’s nm normalised emittance ε_n seen in PIC simulations [3].
  - Density downramp injection: ~ 100 nm normalised emittance seen in PIC [4,5], relatively simple.
  - $B \propto n_e$ scaling [6].



Trojan Horse: A moderately intense, short-pulse laser injects a low emittance beam via localised ionisation injection, from [3].



The reduced phase velocity at the wakefield rear traps fast electrons. **B**-field at rear acts to reduce their transverse momentum and ε_n.

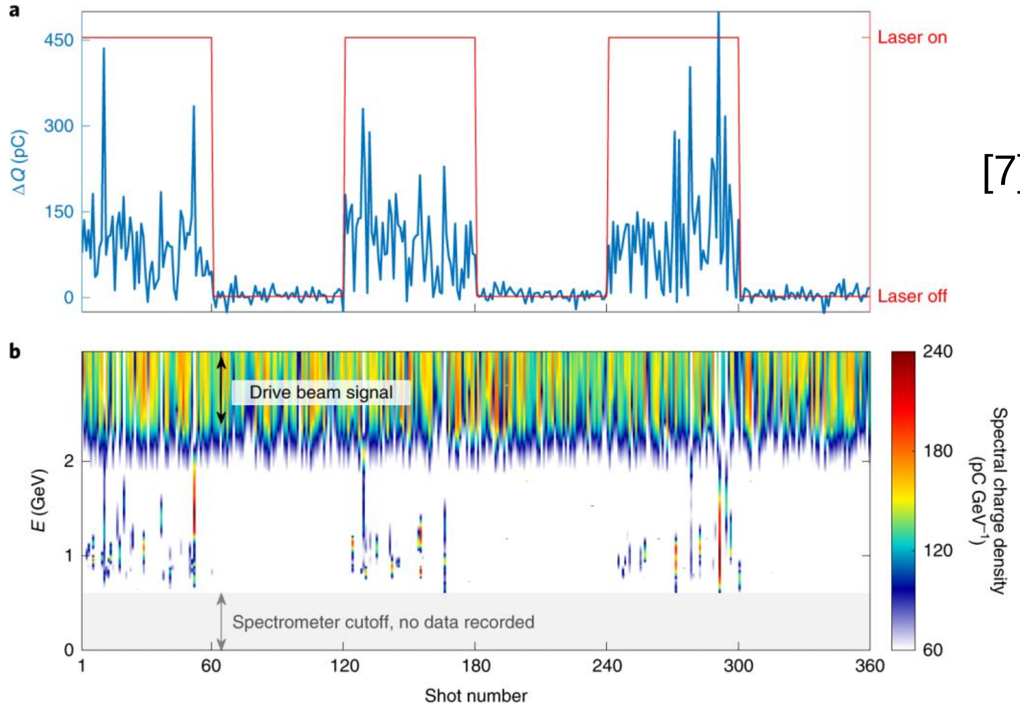
[3] B. Hidding et al., PRL, 2012, https://doi.org/10.1103/PhysRevLett.108.035001
[4] M. C. Thompson et al., PRAB, 2004, https://doi.org/10.1103/PhysRevSTAB.7.011301
[5] X. Xu et al., PRAB, 2017, https://doi.org/10.1103/PhysRevAccelBeams.20.111303
[6] C. Zhang et al., PRAB, 2019, https://doi.org/10.1103/PhysRevAccelBeams.22.111301

Previous Results

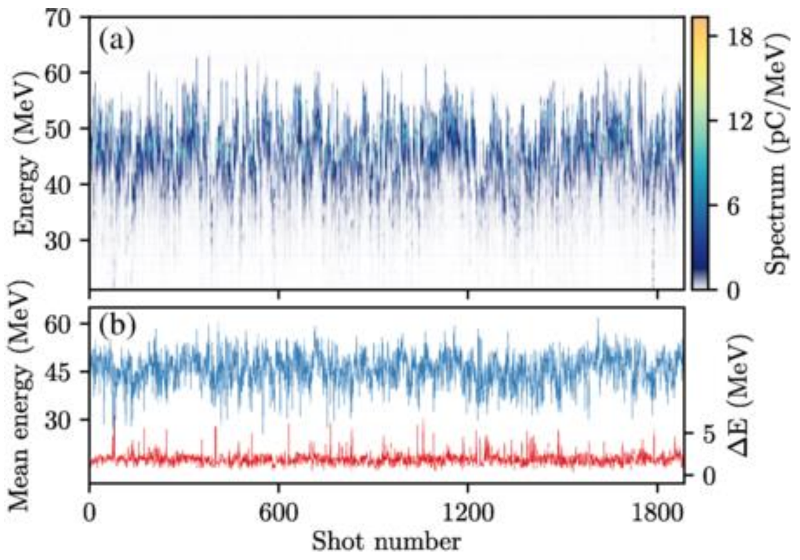
- Plasma photocathode [7]: ~ 1 GeV acceleration (0.5 m), estimated ε_n = 1.5 mm-mrad, dQ/dE ~ 0.2 pC/MeV.
- Optically generated downramp injection [8]: ~ 50 MeV acceleration (3 cm), dQ/dE ~ 10 pC/MeV, ε_n = 9 mm-mrad, 95% injection probability.

Challenges

- Simultaneously produce high dQ/dE, low ε_n bunches with high stability.
- Goal: Measure a higher 3D brightness than the drive bunch ($dQ/dE/\varepsilon_{n,x}$): „Brightness Transformer“.
- Likely $\varepsilon_{n,y}$ $O(\varepsilon_{n,x})$ and σ_t preserved- indicative of 6D brightness increase.



[7]



[8]

[7] A. Deng et al., Nat. Phys, 2019, https://doi.org/10.1038/s41567-019-0610-9
[8] A. Knetsch et al., PRAB, 2021, https://doi.org/10.1103/PhysRevAccelBeams.24.101302

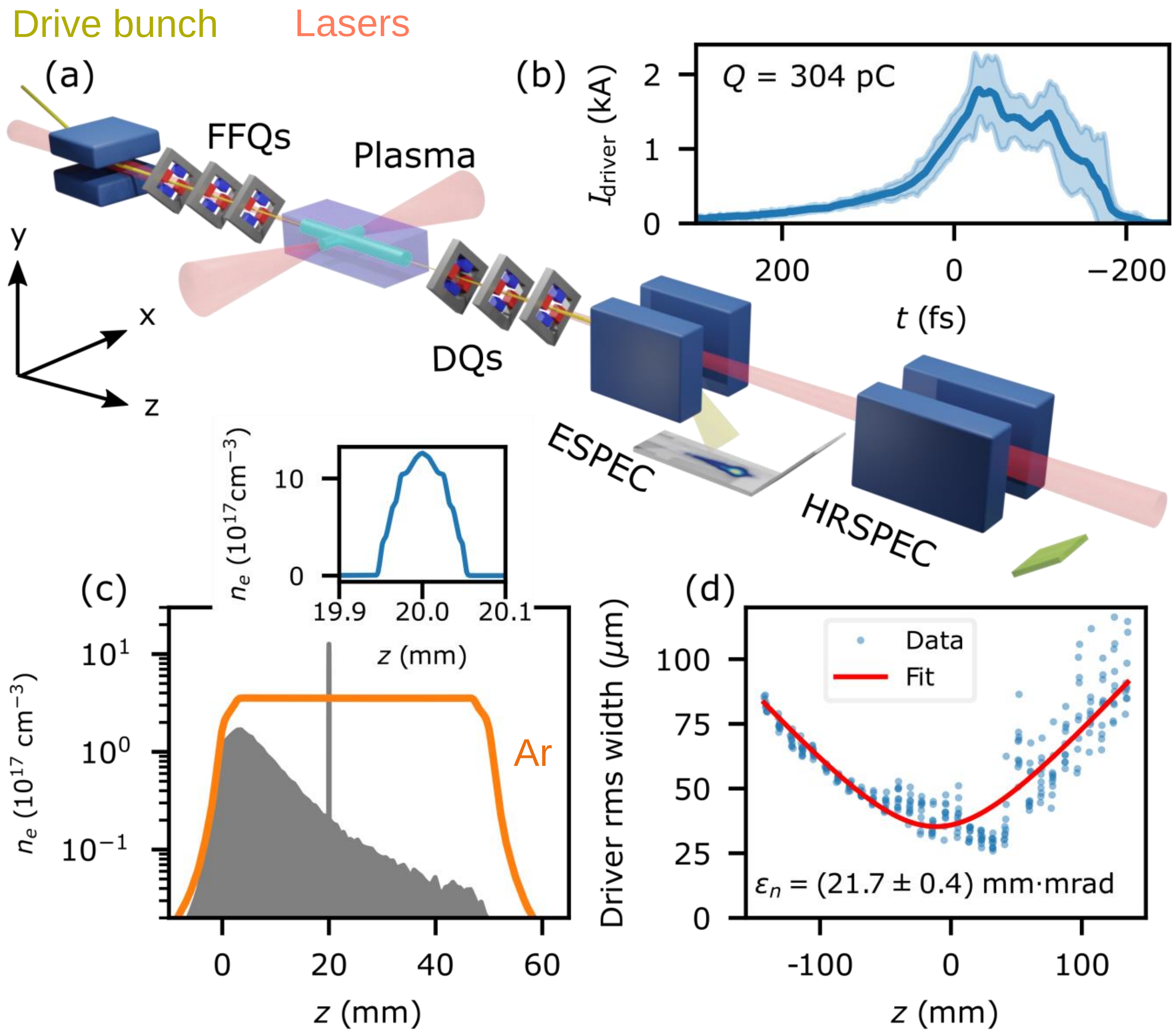
Experimental Setup

Driver

- (304 ± 2) pC, (1.9 ± 0.2) kA.
- 689 MeV, peak dQ/dE = 47 pC/MeV.
- ε_n = 20 mm-mrad (compressed)
- $B_{3D,driver}$ = 2.4 pC/MeV/mm-mrad (from 2 imaging spectrometers: broadband and high-resolution)

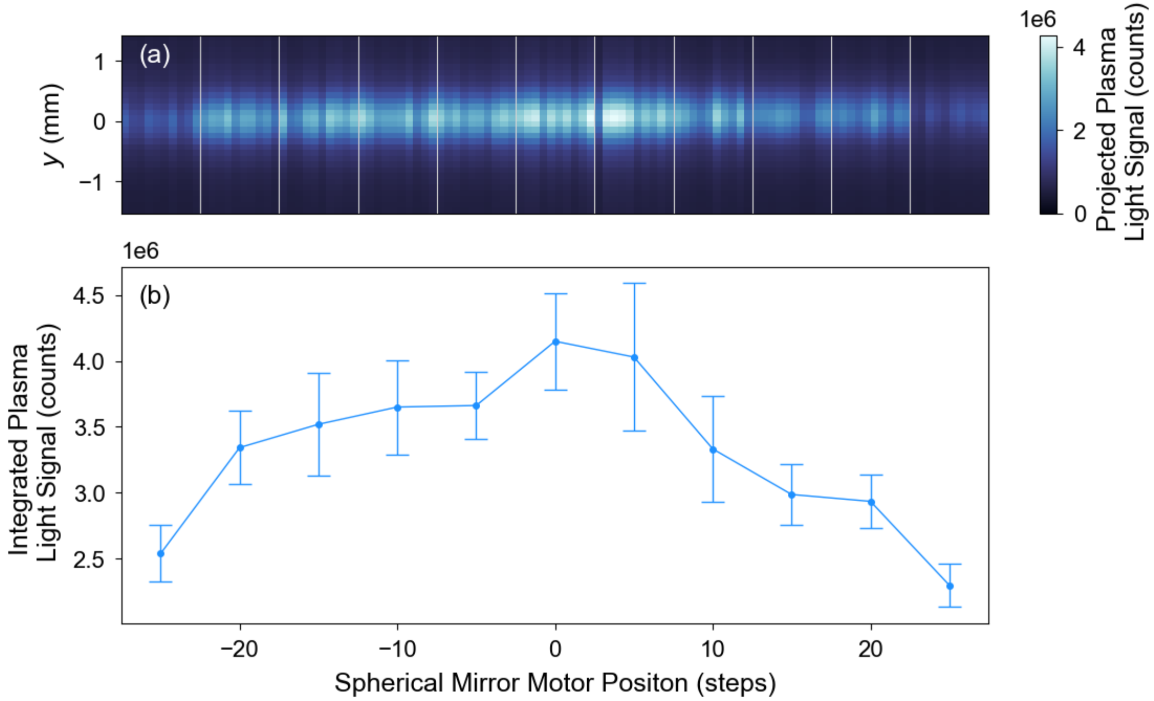
Plasma

- Ionisation defocussing was an issue, however injected beams were rapidly accelerated to relativistic energies (n_e ~ 2x10^{16} cm^{-3}).
- Transverse laser ionises small region to Ar^{3+} or Ar^{4+}, creating a steep density downramp for injection.

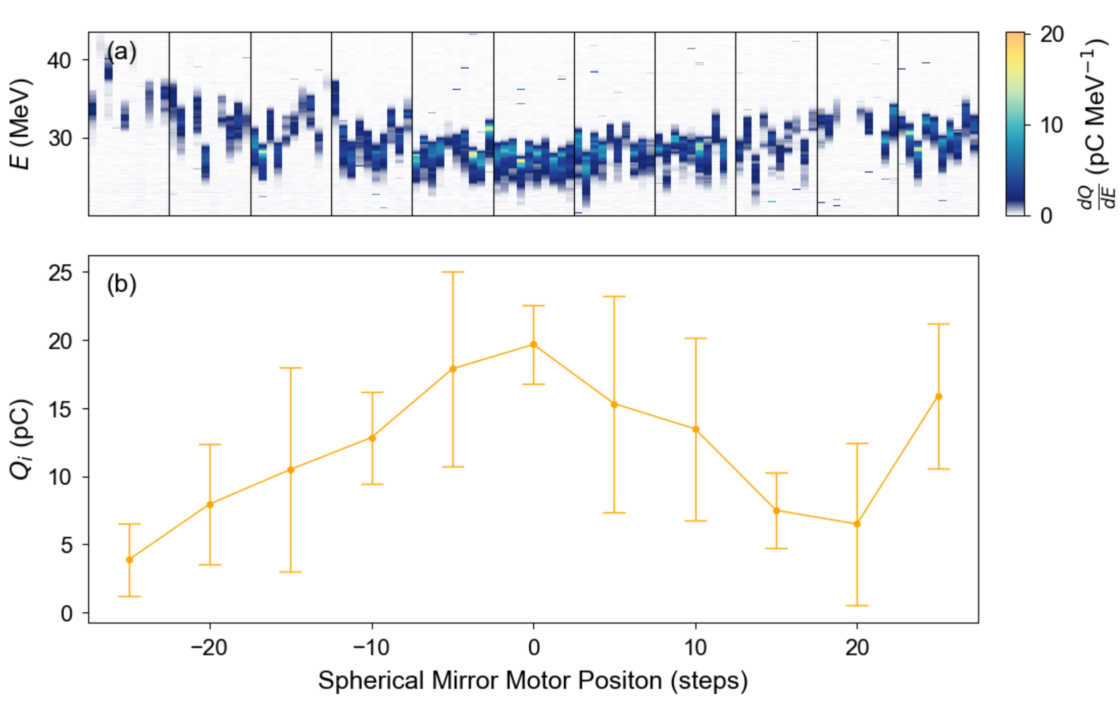


Alignment

- Initial spatial and coarse temporal laser-electron bunch overlap via OTR screens.
- Fine temporal overlap (<0.5 ps, synchronised) via the plasma glow technique [11,12].



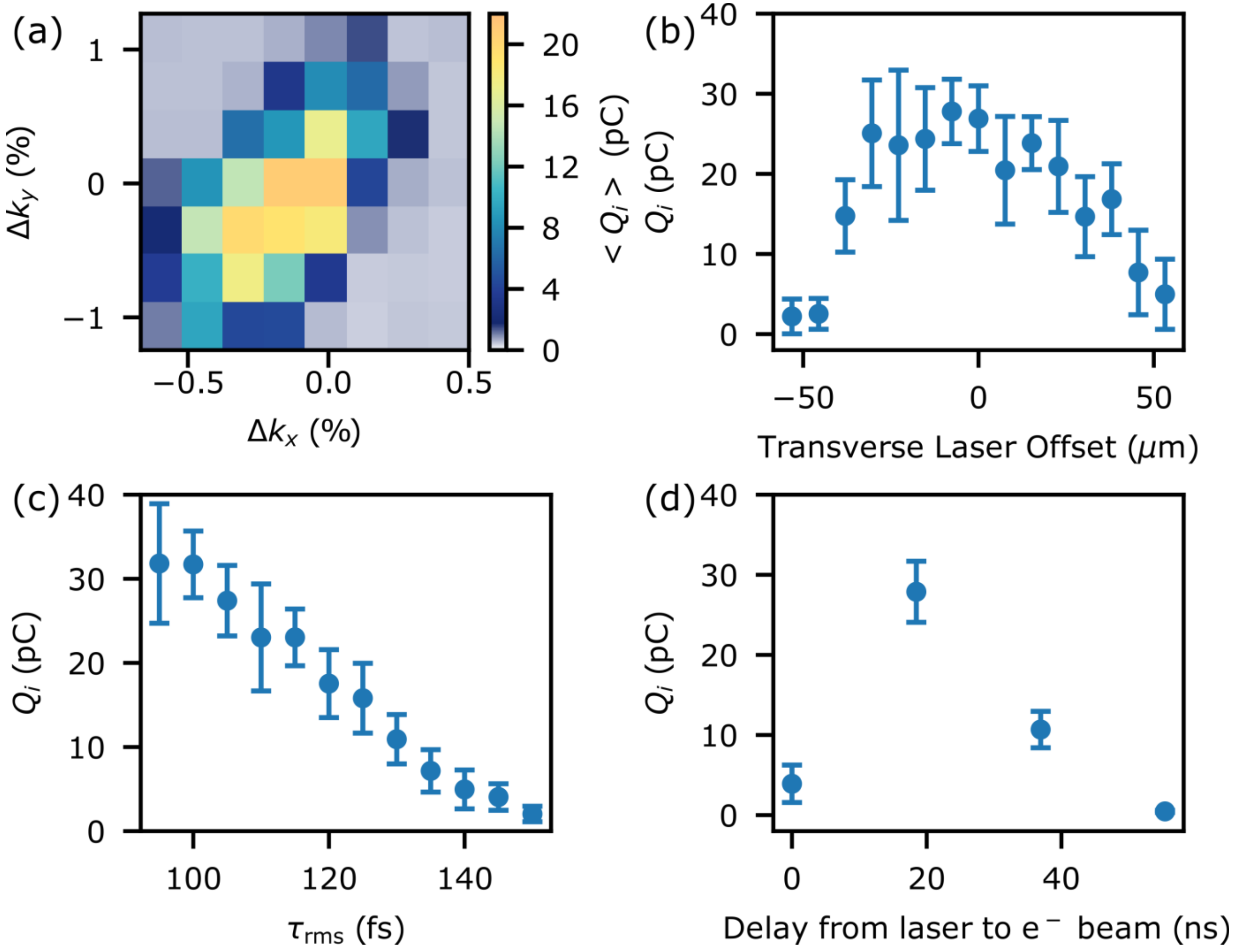
- Spatial overlap was maintained by adjusting the longitudinal laser pointing to maximise the plasma glow signal.
- This also maximised the injected charge.



[11] P. Scherkl et al., PRAB, 2022, doi.org/10.1103/PhysRevAccelBeams.25.052803
[12] E. Adli et al., NJP, 2016, iopscience.iop.org/1367-2630/18/10/103013

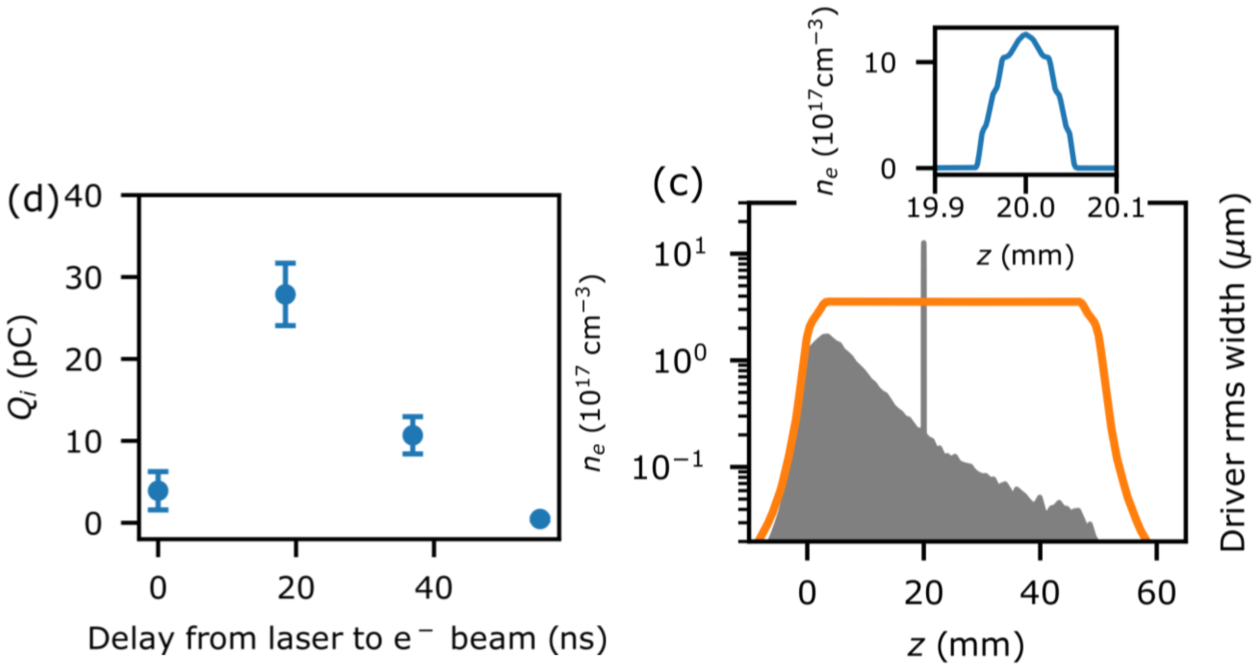
Results: Dependencies of Injected Charge

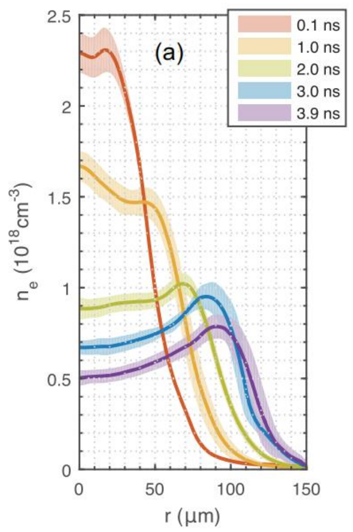
- Optimised injected charge: $Q_i \propto dQ_i/dE$ here.
- Injection only when the transverse laser is present.
- 4 key controls:
  - Focal location of driver bunch (0.1% level)
  - Transverse laser offset – order 10 μm tolerance.
  - Driver duration: higher current = more injected charge. Minimum current for injection (steep ramp) ~ 1.3 kA. ~ Linear scaling of Q_i with I.
  - Delay from laser to electron bunch – many ns required – suggests hydrodynamic motion is important.



Results: Understanding Dependencies on the Downramp

- Injection is only from the density spike. Its evolution changes Q_i(delay).
- A hot plasma generated by a gaussian laser beam expands radially, initially decreasing the height of the plasma spike.
- Eventually a Sedov-Taylor-like shock wave with a steep downramp will form which triggers injection [13-15].
- The shock wave is unsupported & its amplitude decreases in time, terminating injection.





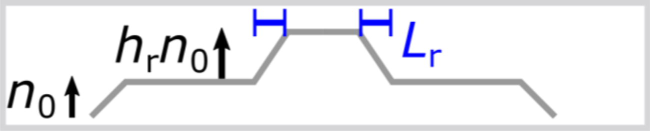
Example evolution from [16].

[13] T.-Y. Chien et al., PRL, 2005, https://doi.org/10.1103/PhysRevLett.94.115003
[14] J. Faure et al., PoP, 2010, https://doi.org/10.1063/1.3469581
[15] F. M. Foerster et al., PRX, 2022, doi.org/10.1103/PhysRevX.12.041016
[16] R. Shalloo et al., PRE, 2018, https://doi.org/10.1103/PhysRevE.97.053203

Results: Understanding Dependencies on the Downramp

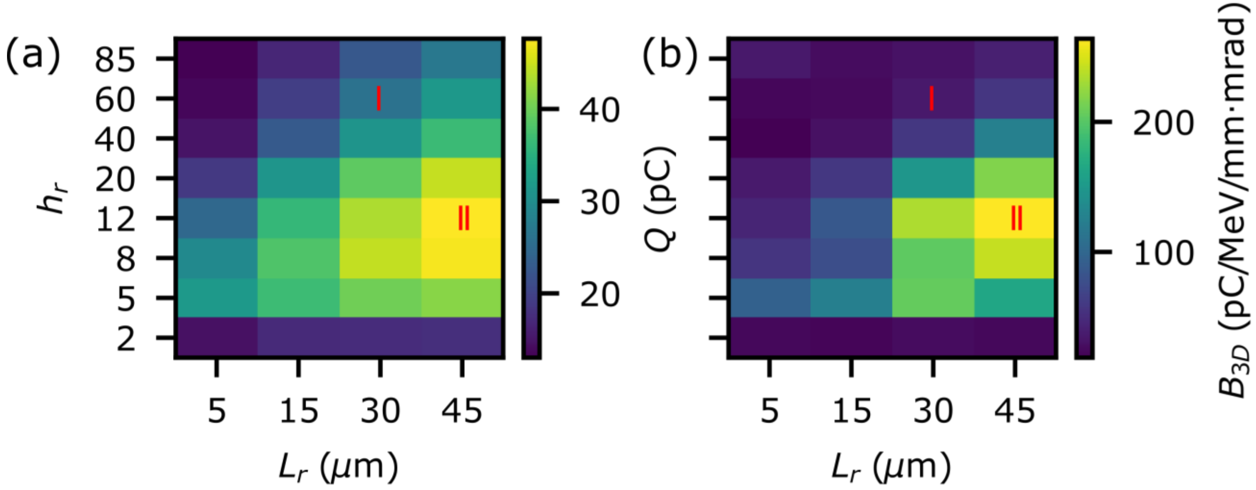
Simplified PIC Simulations

- Do not know the initial conditions well enough for MHD simulations.
- Investigated the effect of ramp height h_r and length L_r on injection using FBPIC [17].
- Gaussian driver with 304 pC charge, I_{pk} = 1.9 kA, ε_n = 20 mm-mrad and σ_r = 16 µm.
- A 2D scan of L_r and h_r was performed.



10 mm plasma simulation, flat top length = 40 µm.

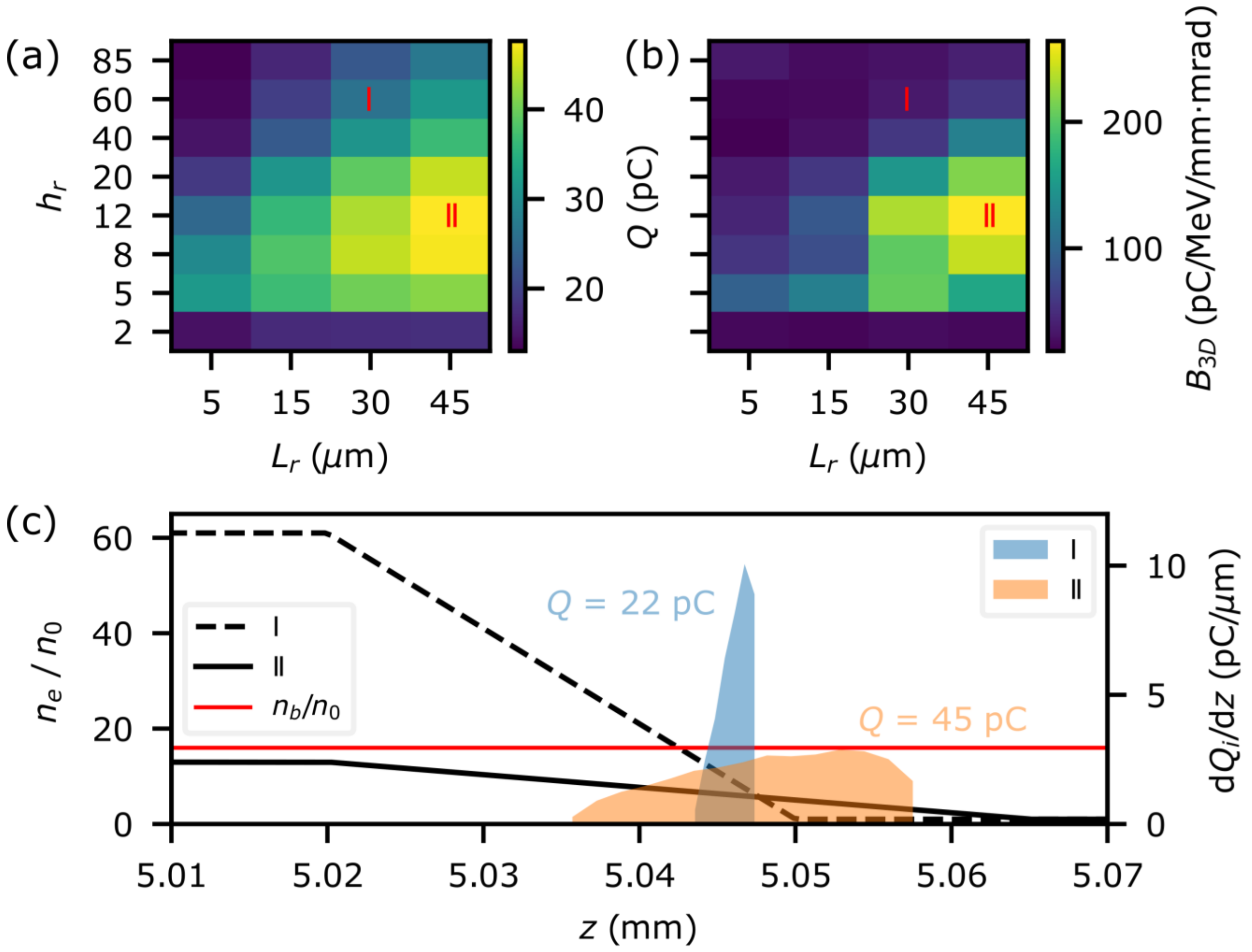
$n_0 = 2\text{x}10^{16}$ cm^{-3}, ~ experimental driver bunch.



[17] R. Lehe et al., CPC, 2016, https://doi.org/10.1016/j.cpc.2016.02.007

Results: Downramp Insights from PIC Simulations

- Longer ramps inject more charge.
- Emittance ~ constant at 0.4-0.5 µm for $Q_i > 20$ pC.
- Optimum ramp height is not the steepest.
- To drive a wakefield require $n_b > n_e$, so injection is only possible in the last part of tall ramps.
- However, it is advantageous for Q_i and B to have $n_b \sim n_e$ in the ramp.
- Most previous work has been done at $h_r \sim 1$ [18,19]



[18] D. Ullmann et al., Phys. Rev. Research, 2021, doi.org/10.1103/PhysRevResearch.3.043163
[19] G. Wittig et al., PRAB, 2015, doi.org/10.1103/PhysRevSTAB.18.081304

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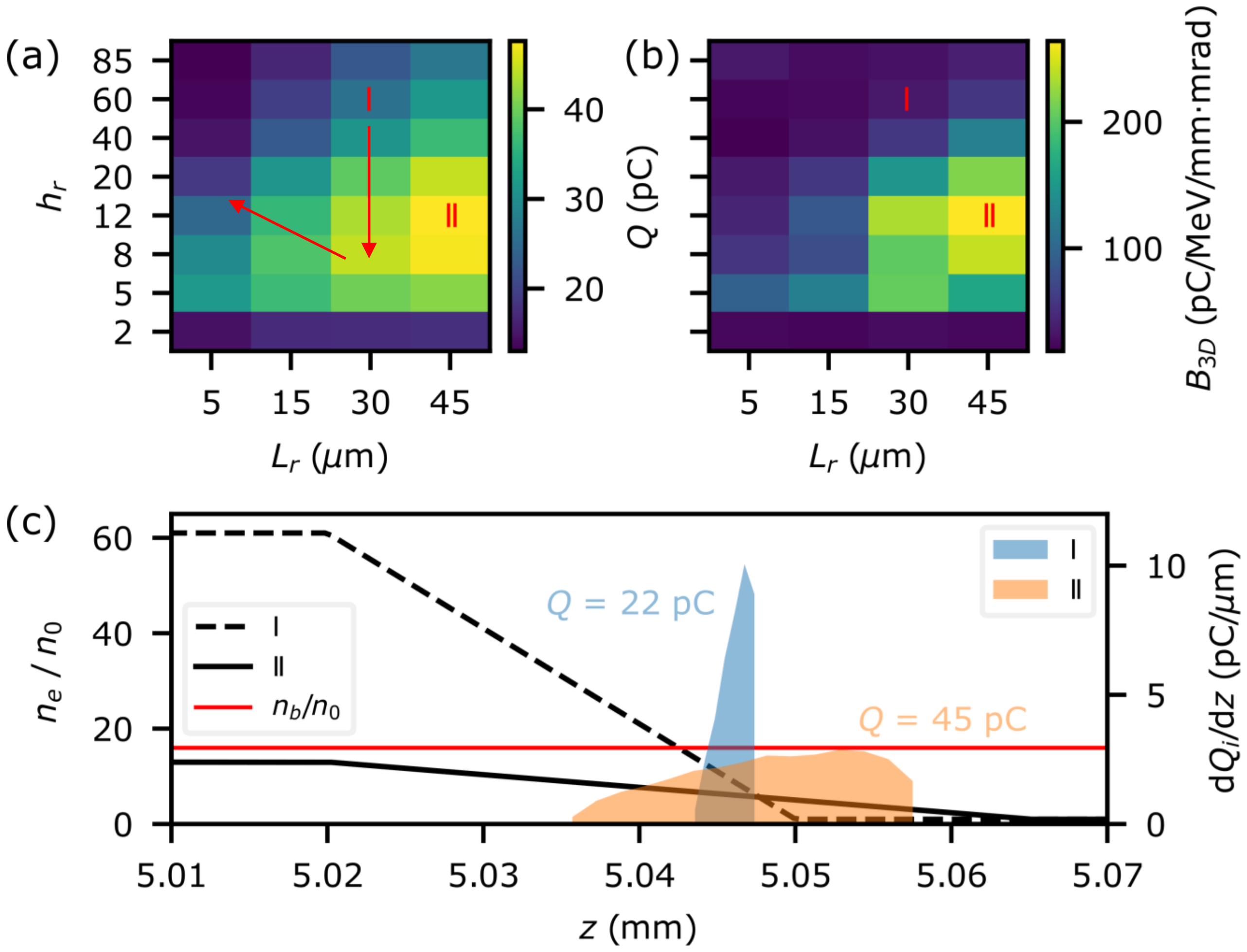
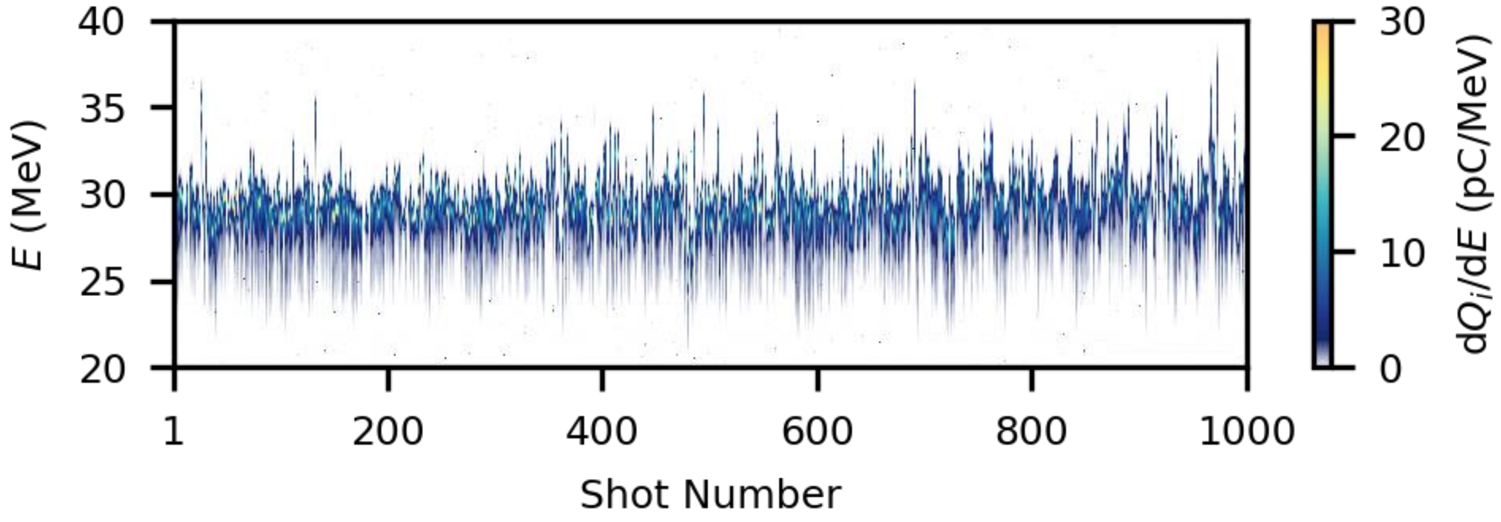
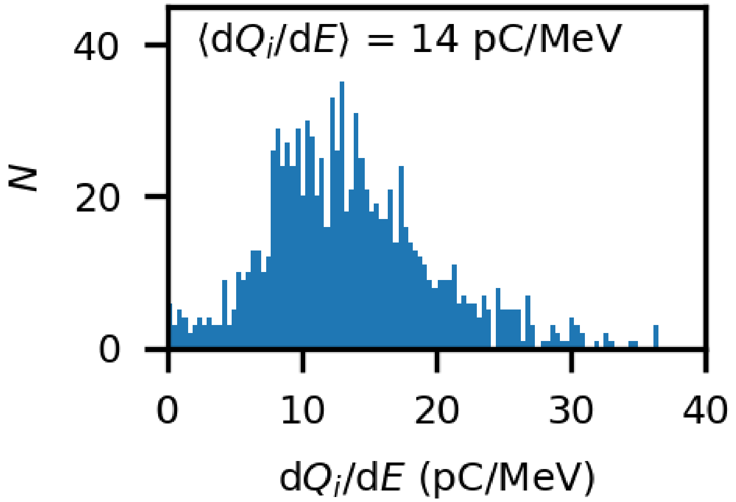
- Optimum ramp height is not the steepest.
- To drive a wakefield require $n_b > n_e$, so injection is only possible in the last part of tall ramps.
- However, it is clear advantageous for charge and brightness to have $n_b \sim n_e$ in the ramp.
- Most previous work has been done at $h_r \sim 1$ [18,19]
- Likely shape of ramp evolution shown with arrows, explaining increase then decrease of Q_i.



[18] D. Ullmann et al., Phys. Rev. Research, 2021, doi.org/10.1103/PhysRevResearch.3.043163
[19] G. Wittig et al., PRAB, 2015, doi.org/10.1103/PhysRevSTAB.18.081304

Results: Stability (Experiment)



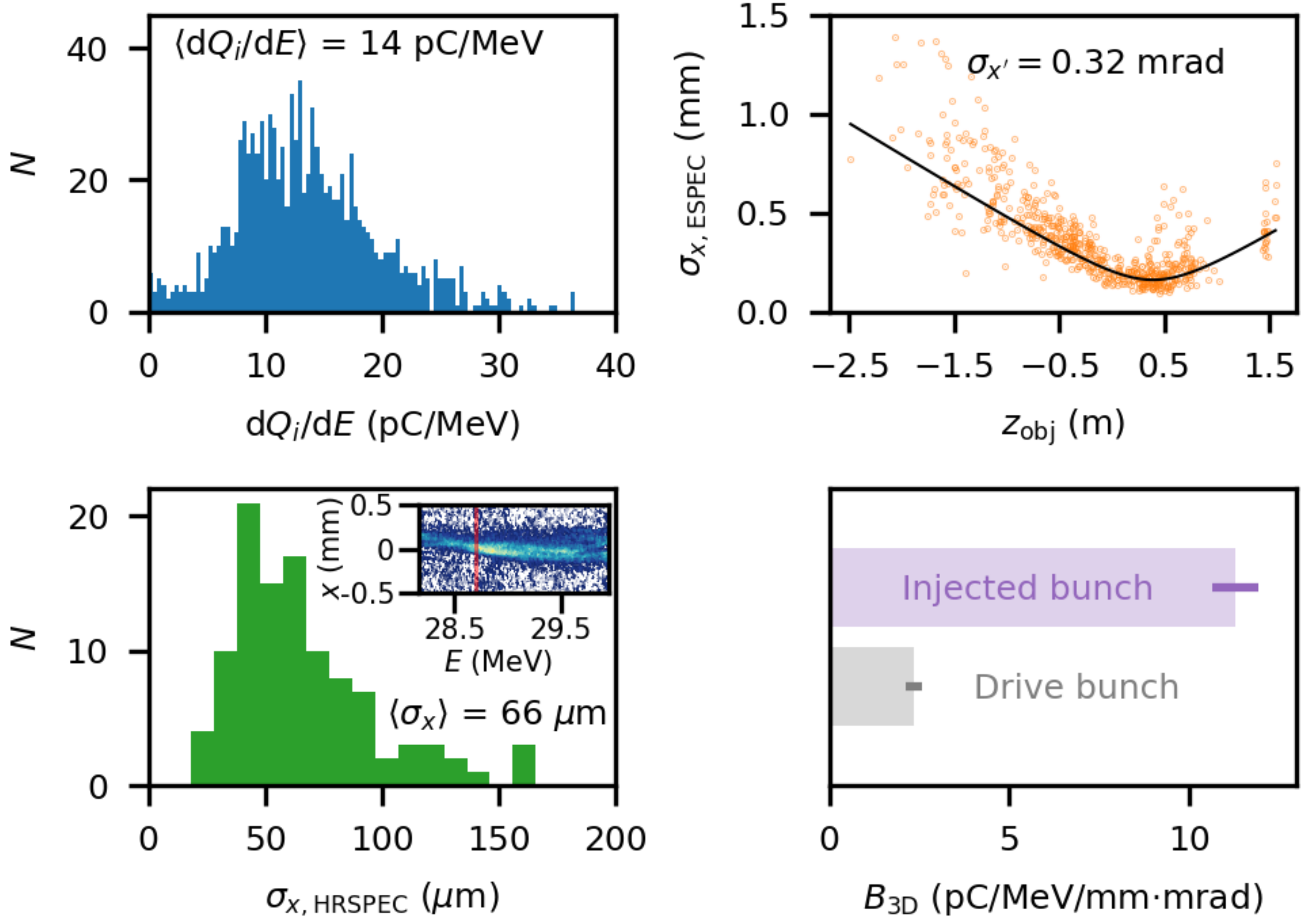


- Electron energy spectra: 1000 shots at 2 Hz.
- Mean σ_E = 1.3% FWHM.
- $\langle Q_i \rangle$ = (19 ± 7) pC.

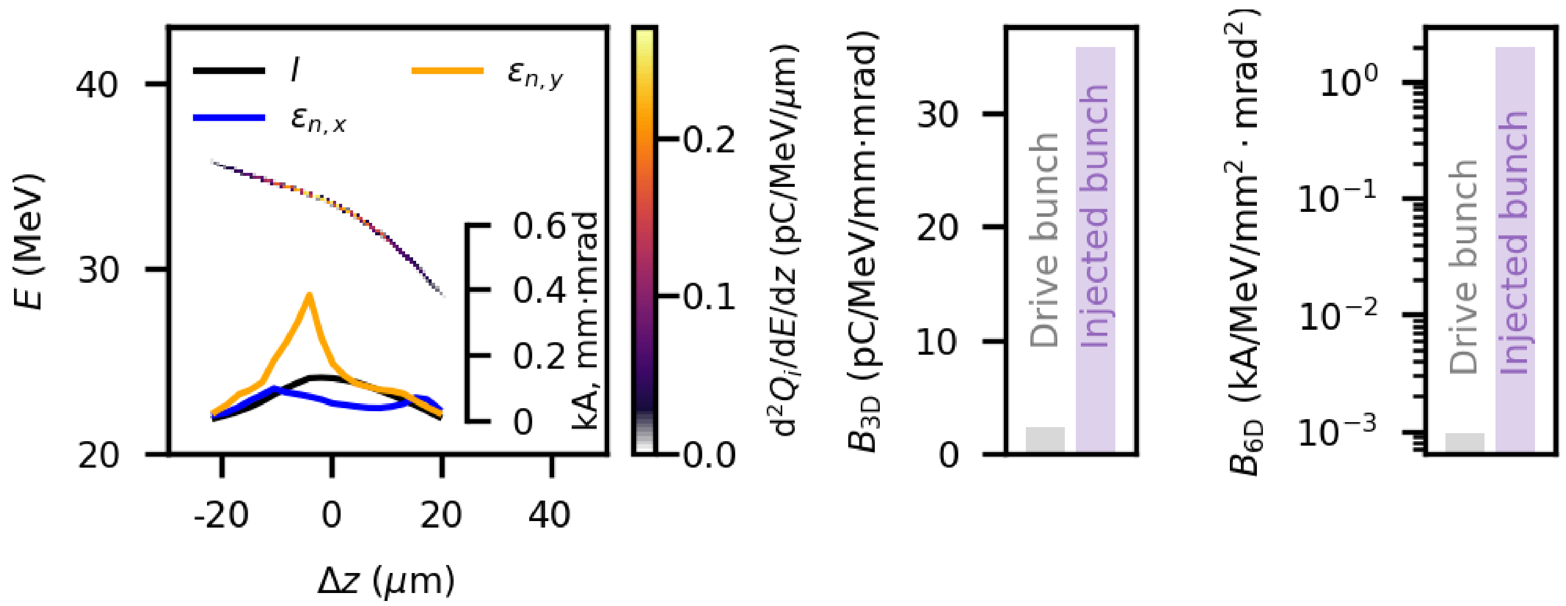
- $\langle \mathrm{d}Q_i/\mathrm{d}E \rangle$ = (14 ± 6) pC/MeV.
- Max. 36 pC/MeV, close to that of the driver (47 pC/MeV).

Results: Emittance & Brightness Measurements

- Imaging object plane scan on the ESPEC to find the divergence: 0.32 mrad.
- Insufficient resolution to find $\sigma_{x,min}$.
- We made 106 high-resolution σ_x measurements- object plane scan not possible due to small jitters.
- Slice width (chromatic imaging): $<\sigma_x>$ = (66 ± 3) µm (standard error), mode σ_x = 43 µm.
- $\langle \varepsilon_{n,x} \rangle = \gamma\beta \langle \sigma_{x,min} \rangle \langle \sigma_{x'} \rangle$ = (1.2 ± 0.1) mm-mrad (mode 0.8 mm-mrad).
- B_{3D} = 11.3 pC/MeV/mm-mrad, 4.8 times larger than the driver beam.



Results: 3D PIC Simulations

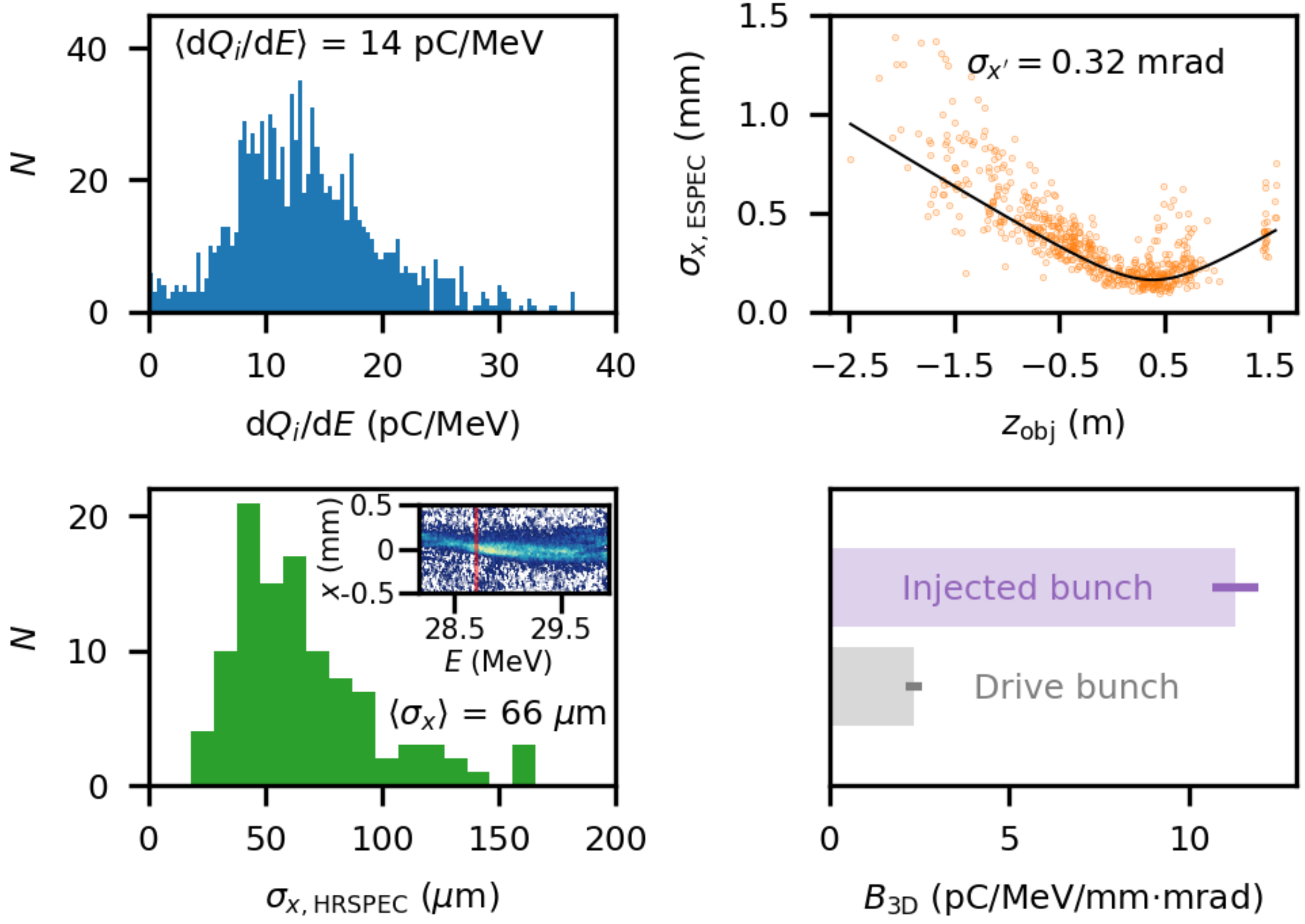


- 3D PIC simulations in WarpX [20] the experimental n_e profile, driver *I* and $\epsilon_{n,x}$.
- 0.2 kA bunch injected.
- Slice emittances between 0.1 - 0.4 mm-mrad. Projected $\epsilon_{n,x}$ = 0.12 mm-mrad, $\epsilon_{n,y}$ = 0.40 mm-mrad.
- Asymmetric emittance from plasma spike shape.
- Simulated B_{3D} = 42 pC/MeV/mm-mrad is 18 x that of the driver and 3.7 x the experimental value.
- Simulated B_{6D} = 1.3 kA/MeV/mm²/mrad², exceeding that of the driver bunch by 3 orders of magnitude.

[20] A. Myers et al., Parallel Computing, 2021, doi.org/10.1016/j.parco.2021.102833

Conclusions

- Produced high quality bunches from a PWFA using density-downramp injection.
- Per-cent-level energy spread bunches accelerated at ~ 1 GV/m with high spectral density and reproducibility, aided by tailoring the downramp profile with a hydrodynamic expansion technique.
- The emittance of the injected bunch was 1.2 mm-mrad, 17 times lower than that of the driver. Its 3D brightness was 5 times higher.
- A promising step towards generating truly ultrabright bunches from plasma-based injection methods in the future.



Additional Material

Single-Shot Emittance Measurement

Butterfly Technique

- “Single shot object plane scan”.
- There were only a few shots with large enough divergence to measure a significant beam width change with our energy spread.
- This shot had 8 pC/MeV and εn,x = 1.2 mm-mrad, suggesting B3D = 6.7 pC/MeV/mm-mrad, an increase of 2.8 times.