Controlled injection of electrons in a laser wakefield accelerator

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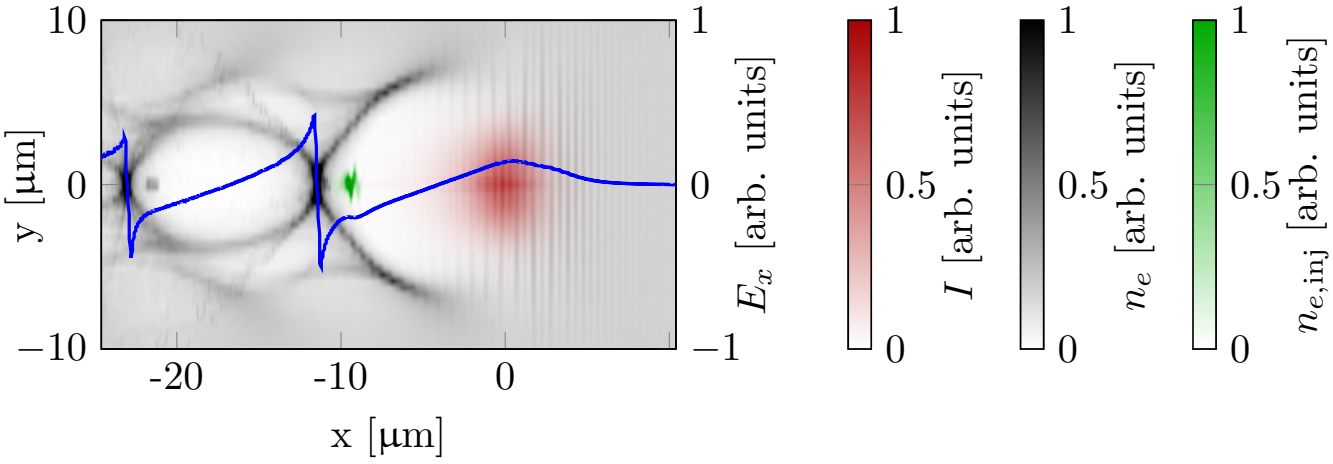
Laser wakefield acceleration

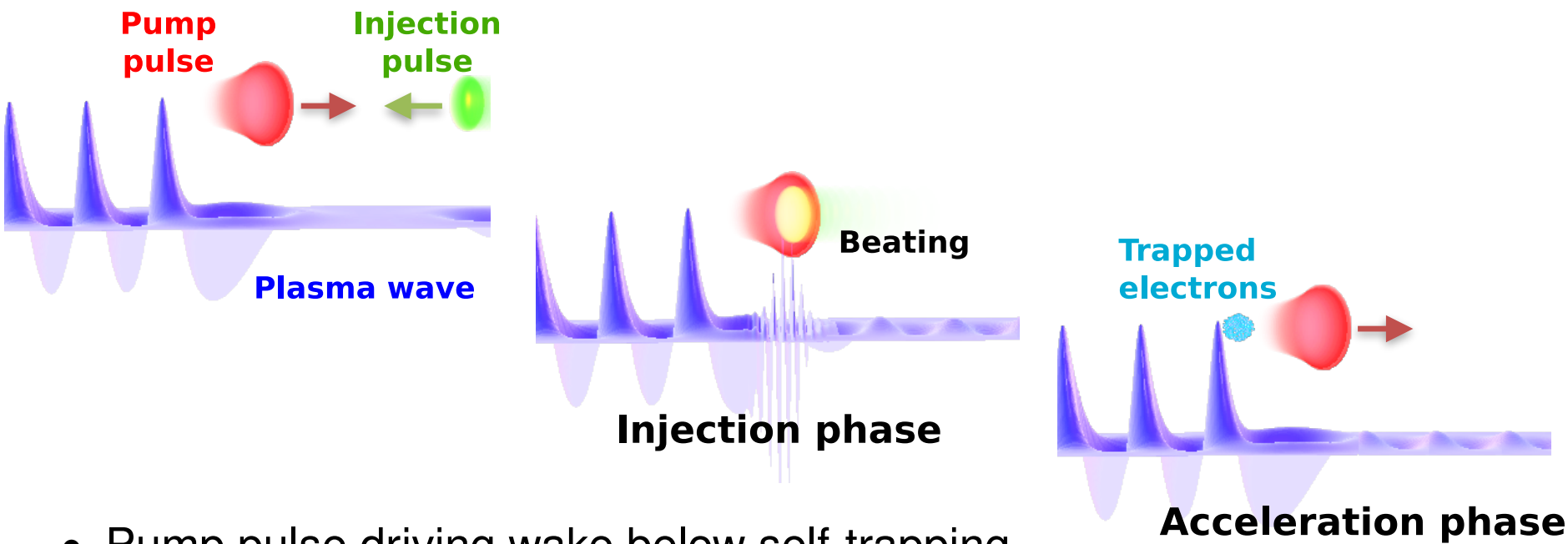


Objective: Controlling injection to improve reproducibility

Outline:

1. Colliding pulse injection
2. Density down-ramp injection

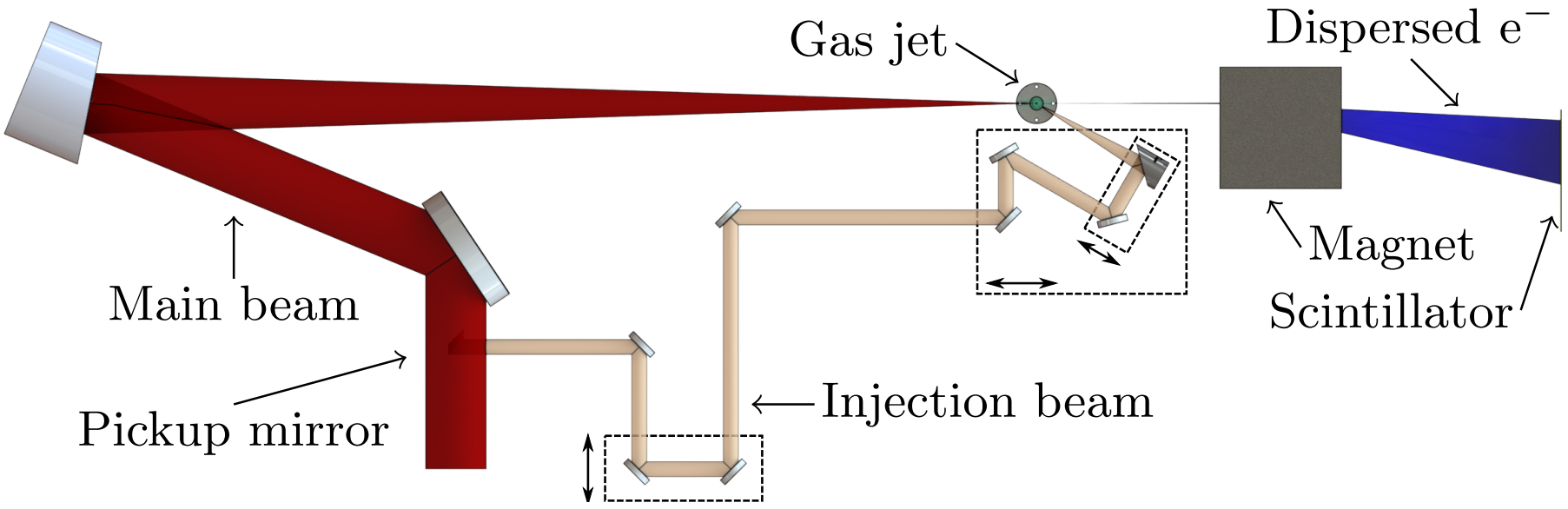
Colliding pulse injection



- Pump pulse driving wake below self-trapping
- Injection pulse beats with pump pulse
- Stochastic heating triggers injection

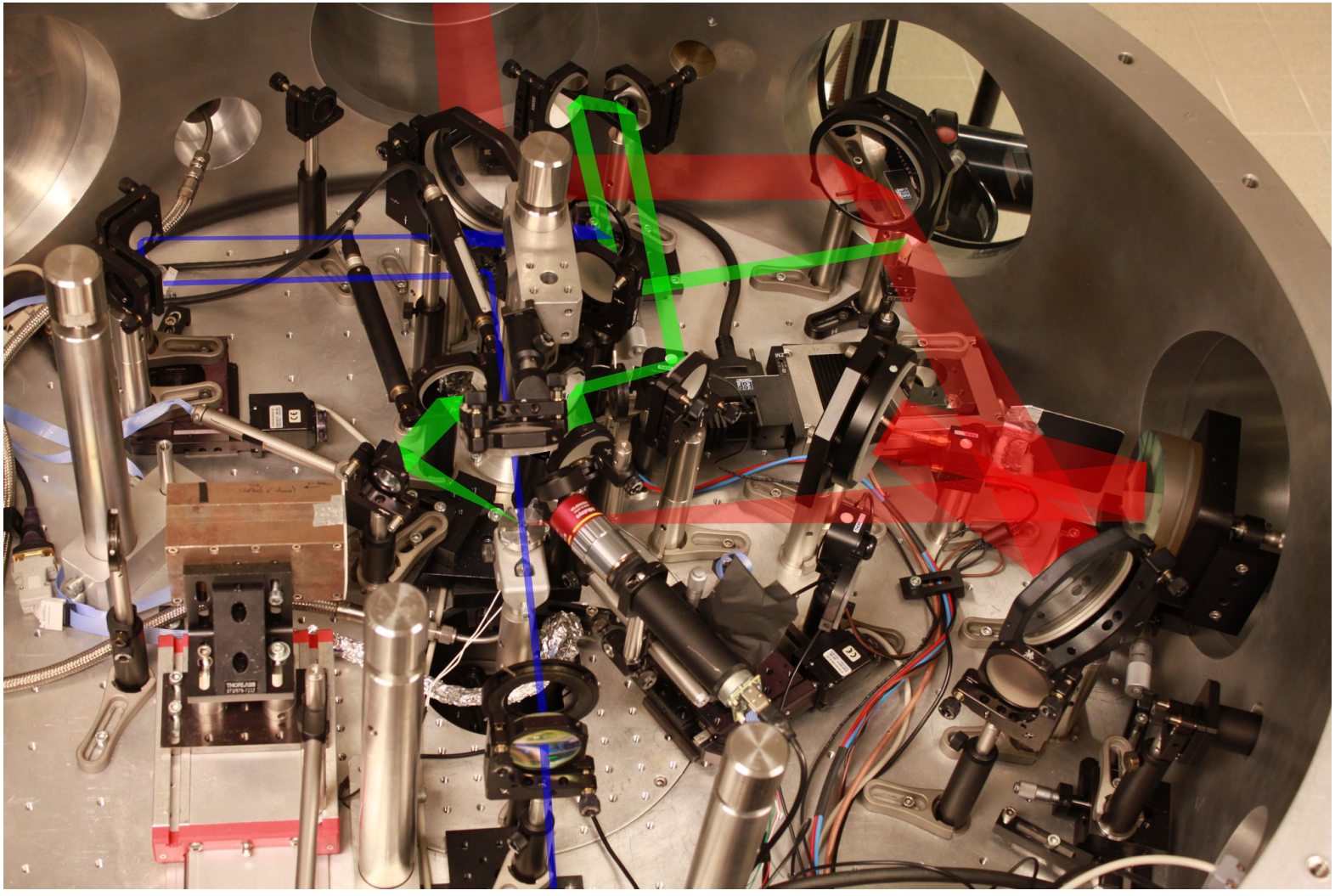
Image courtesy of Clément Rechatin

Colliding pulses in gas jet

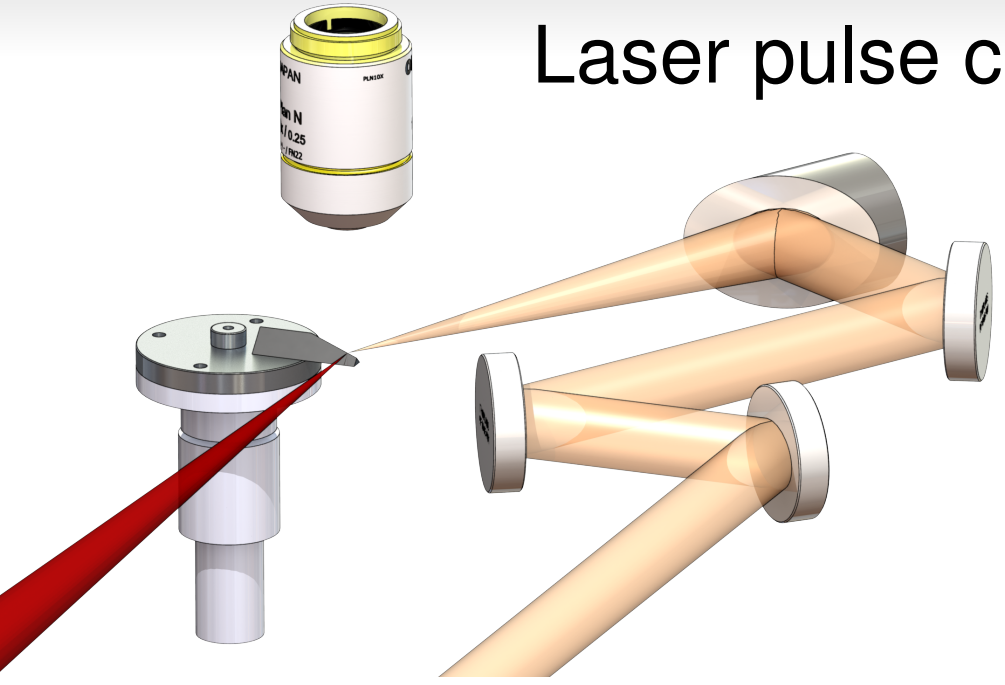


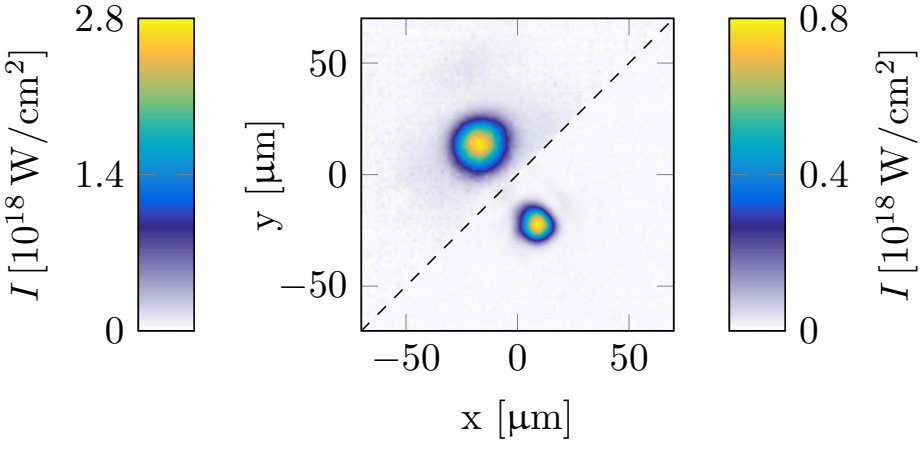
- Small pick-up close to target
- Collision angle $150\,^{\circ}$
- Mounting to allow for scanning parameters
- 2 mm hydrogen gas jet.
- Electron density $n_e \approx 8 \cdot 10^{18}\,\mathrm{cm}^{-3}$

Colliding pulses in gas jet



Laser pulse characteristics





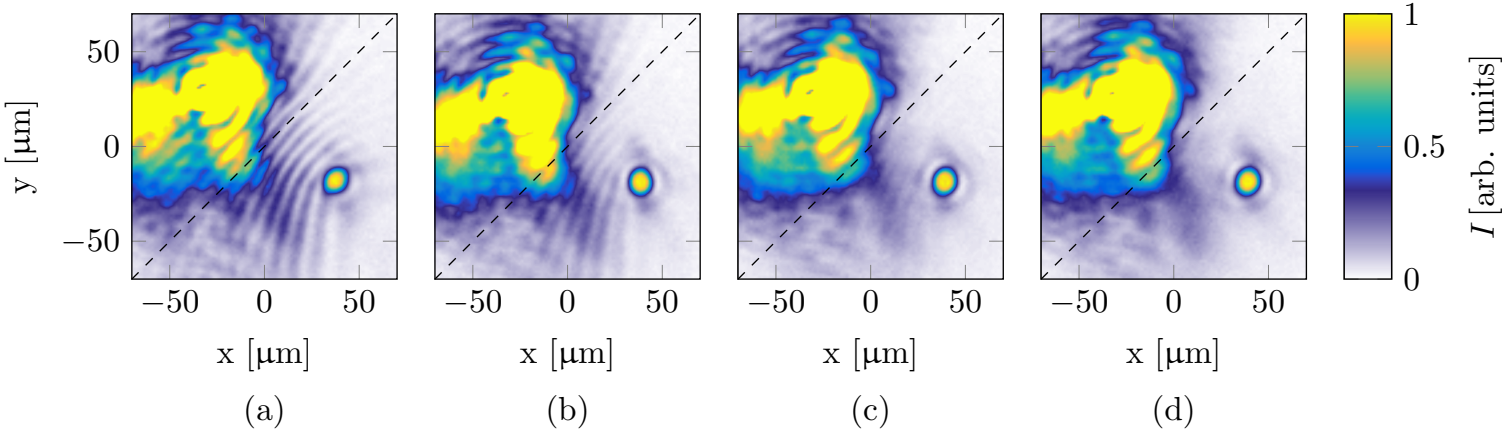
Main pulse

- $E = 470\,\mathrm{mJ}$
- $T_{\mathrm{FWHM}} = 37\,\mathrm{fs}$
- $D_{\mathrm{FWHM}} = 20\,\mu\mathrm{m}$
- $I = 2.8 \cdot 10^{18}\,\mathrm{W/cm^2}$
- $a_0 = 1.1$

Injection pulse

- $E = 42\,\mathrm{mJ}$
- $T_{\mathrm{FWHM}} = 37\,\mathrm{fs}$
- $D_{\mathrm{FWHM}} = 11\,\mu\mathrm{m}$
- $I = 0.8 \cdot 10^{18}\,\mathrm{W/cm^2}$
- $a_0 = 0.3$

Temporal overlap



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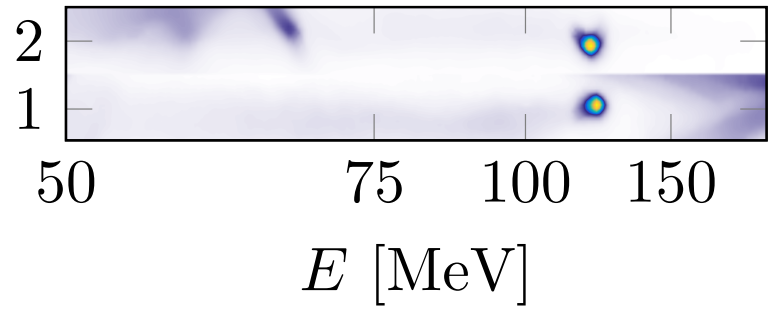
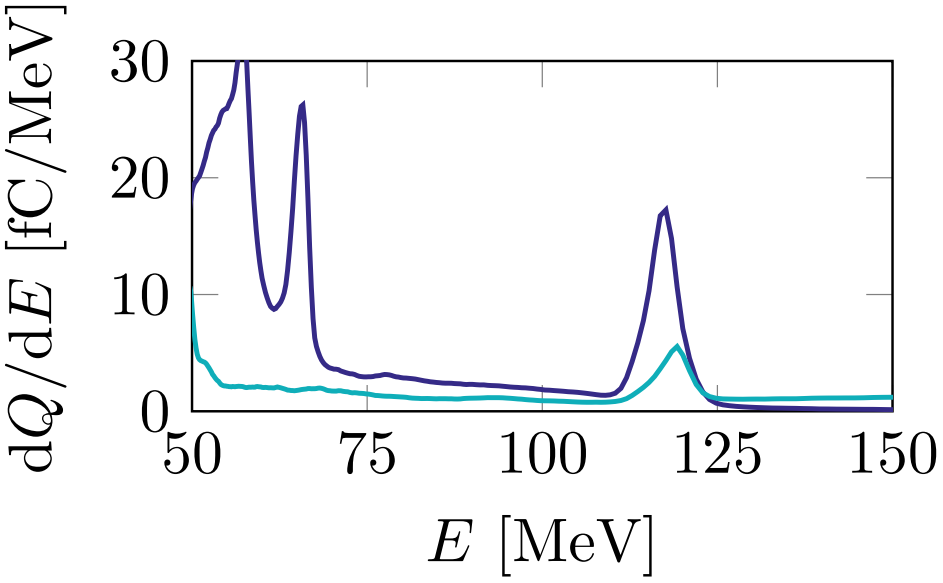
High quality beams

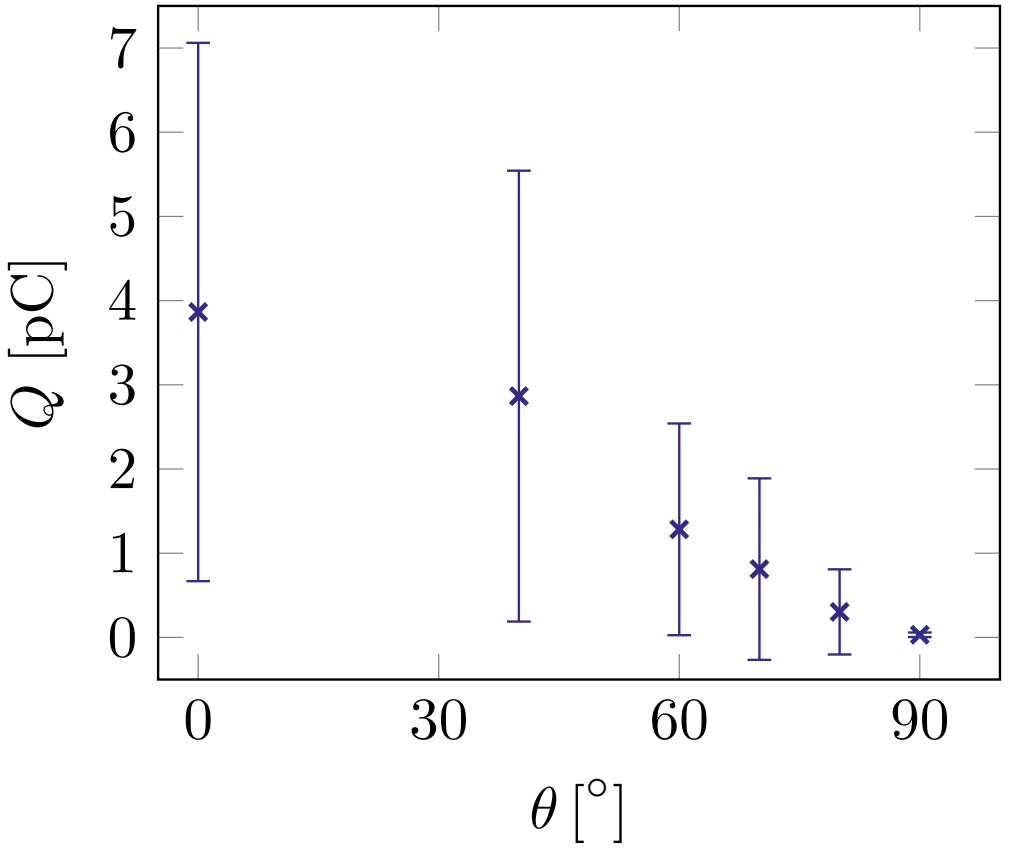


⟵ Dispersed electron beams



- Low divergence $\approx 3\,\mathrm{mrad}$
- Low energy spread $\approx 5\,\mathrm{MeV}$
- Charge $0.1\,\mathrm{pC} - 10\,\mathrm{pC}$

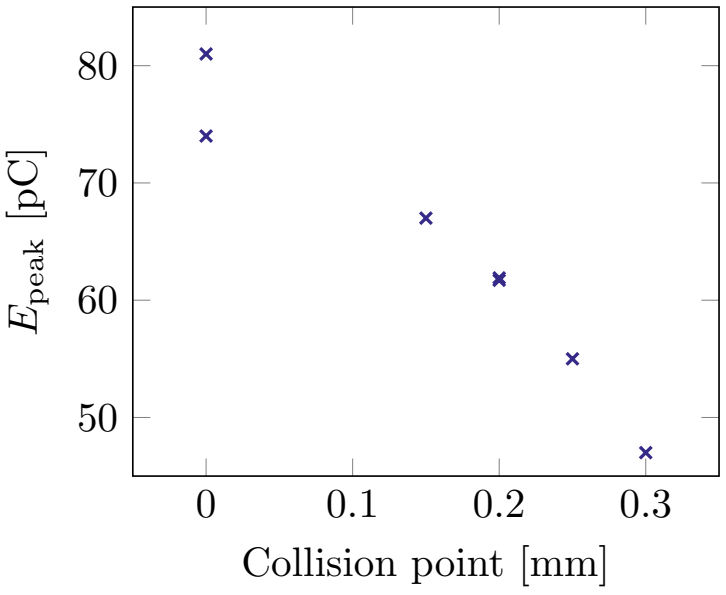
Polarization dependence

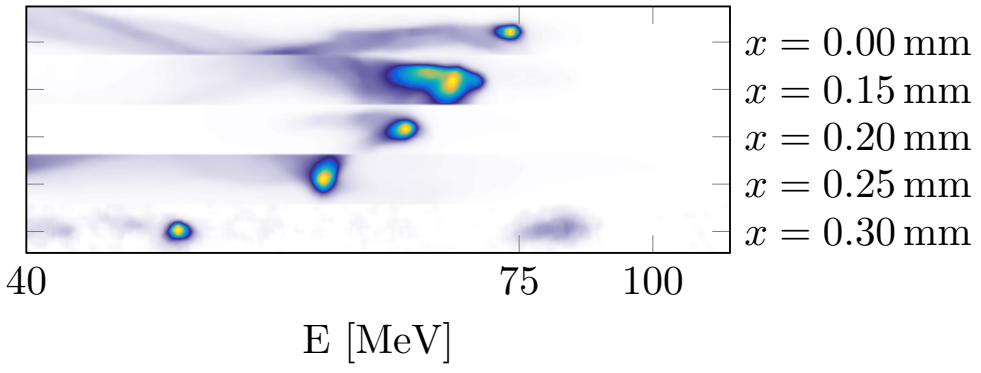


- Large fluctuations, but...
- Clear dependence on the relative polarization of the two pulses

Collision point

Energy tuning



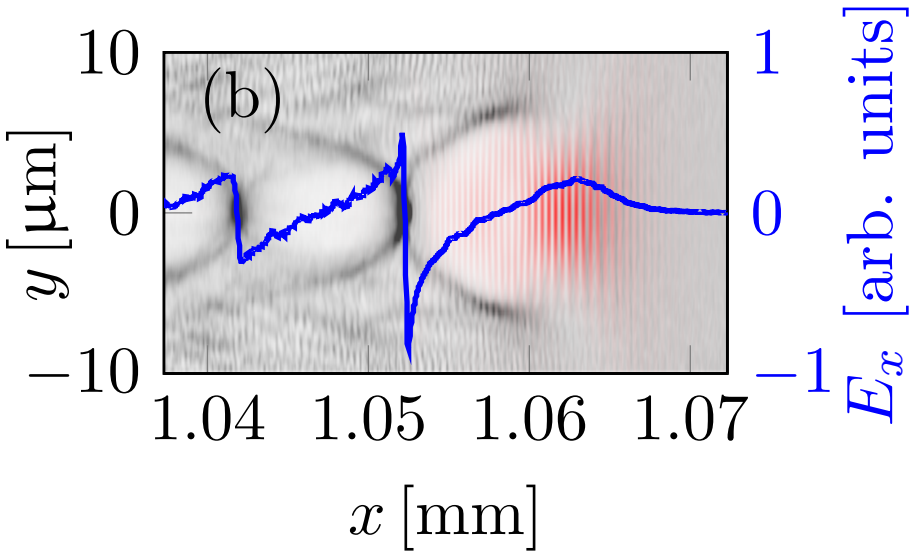


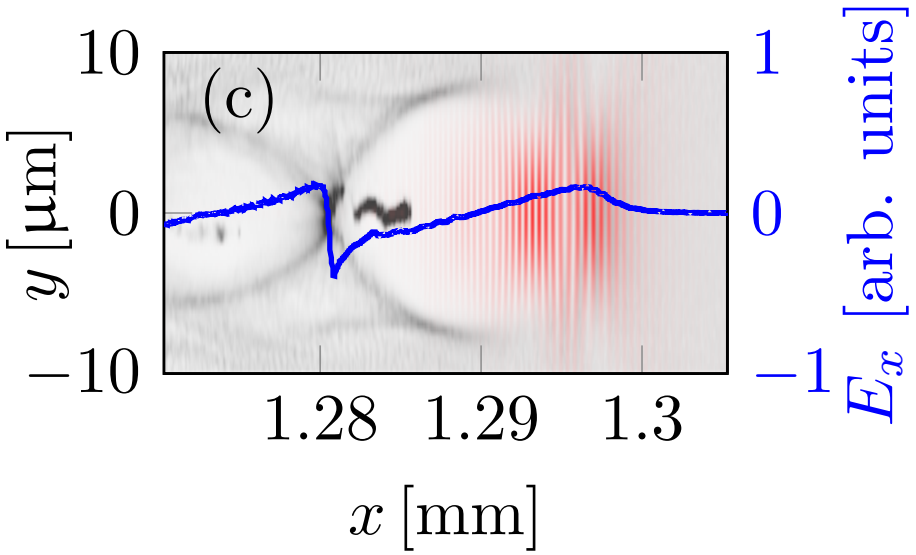
$x = 0\,\text{mm}$ - collision in center of jet

Electron density $n_e = 8 \cdot 10^{18}\text{cm}^{-3}$

- Acceleration length varied by the point of collision
- Effective accelerating field of $150\,\text{MV/mm}$

Density down-ramp injection

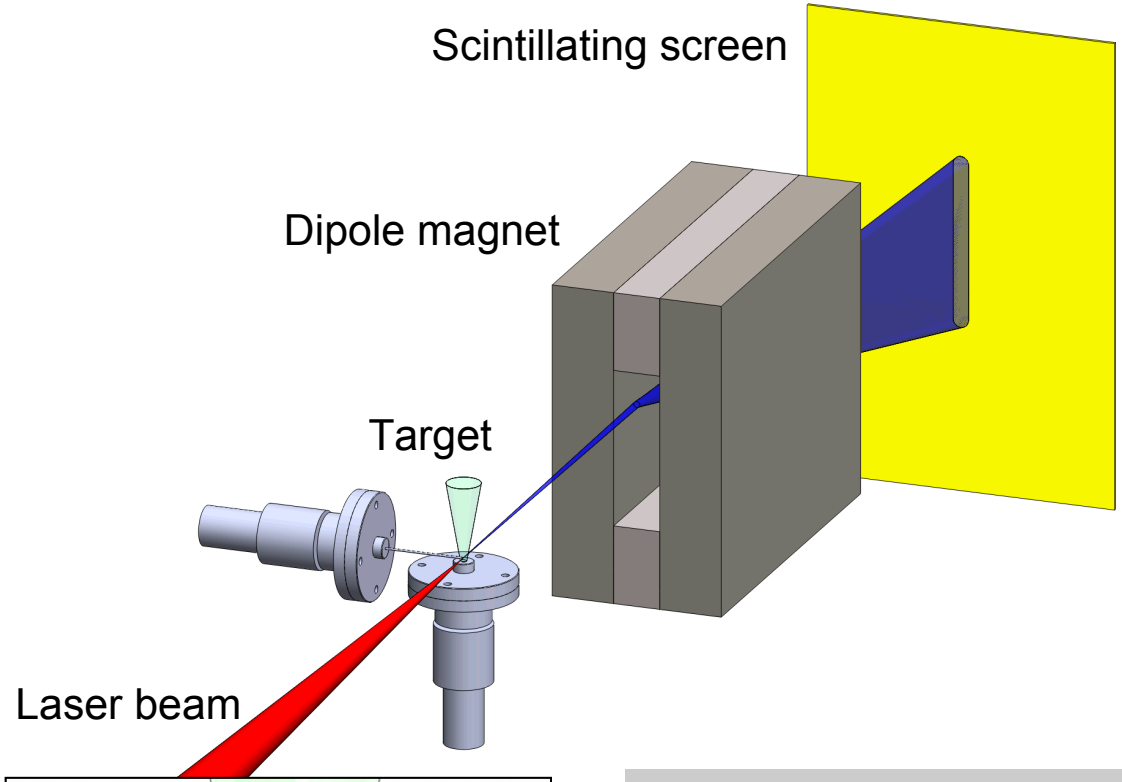




- Wave-breaking as particle velocity approaches phase velocity of the wake
- Wake phase velocity decreases behind the laser pulse in a density downramp

$\Rightarrow$ Lower threshold for trapping

Density down-ramp injection

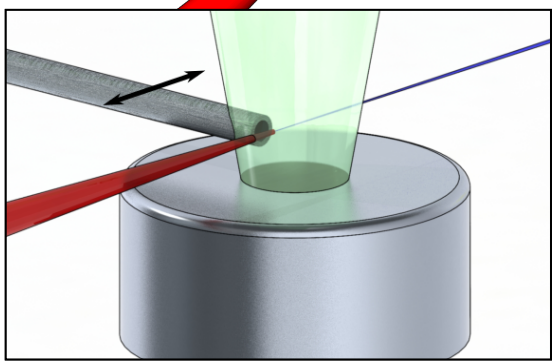


Gas target

- 2 mm gas jet nozzle

  combined with

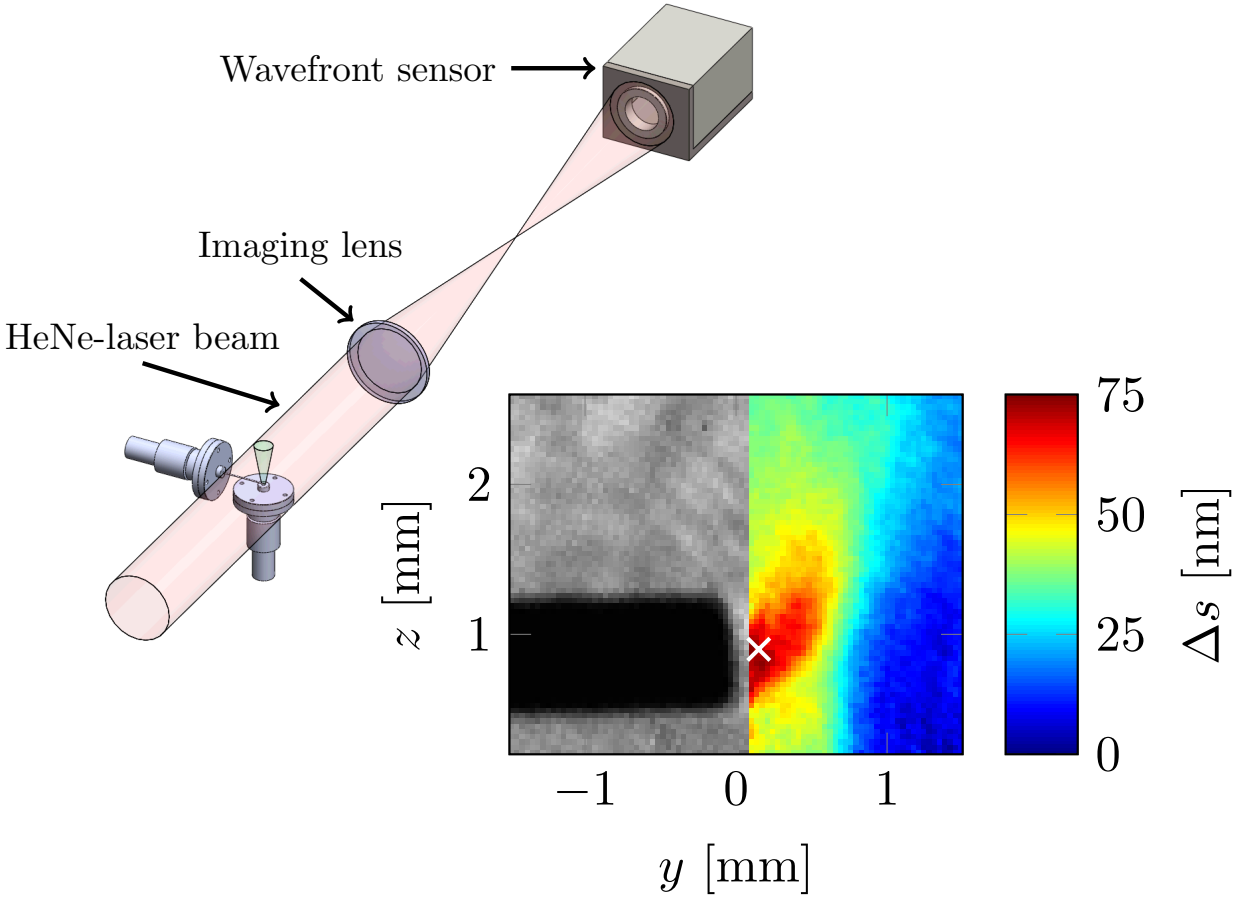
- 0.4 mm narrow tube

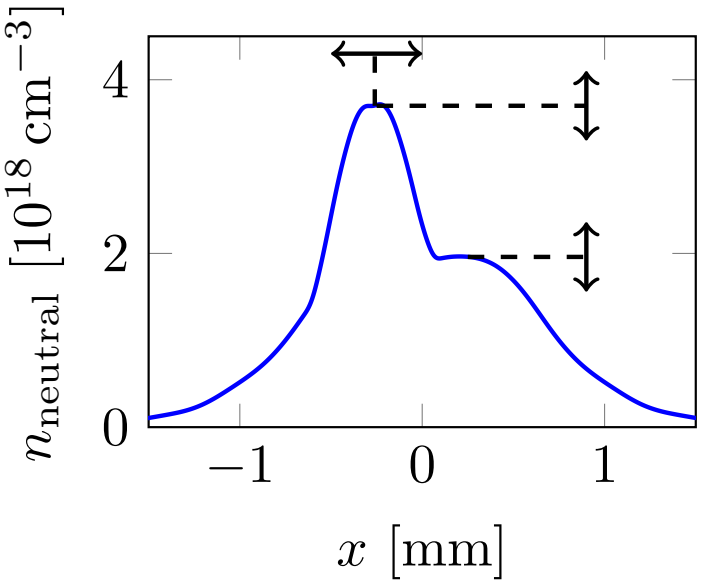


Laser pulse characteristics

- $E = 600\,\mathrm{mJ}$
- $T_{\mathrm{FWHM}} = 40\,\mathrm{fs}$
- $\lambda = 800\,\mathrm{nm}$
- $D_{\mathrm{FWHM}} = 19\,\mu\mathrm{m}$
- $I = 4 \cdot 10^{18}\,\mathrm{W/cm^2}$
- $a_0 = 1.3$

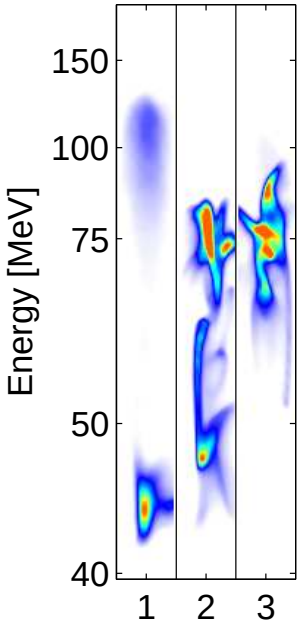
Target characterization





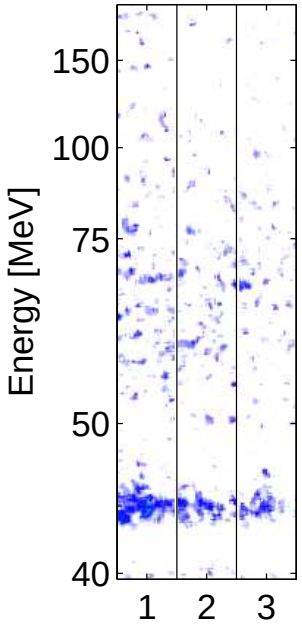
- Phase shift introduced by neutral gas measured using wavefront sensor
- Two regions of controlled density with gradient

Injection in density down-ramp



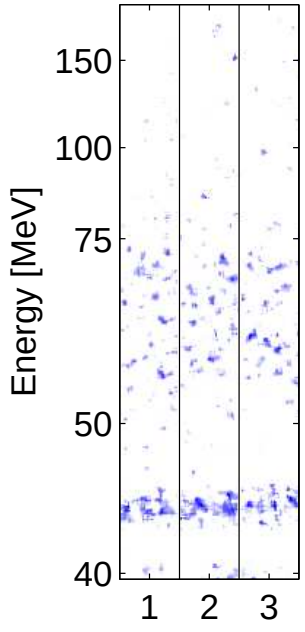
2 mm nozzle

Plateau density:
$13 \cdot 10^{18}\,\mathrm{cm}^{-3}$



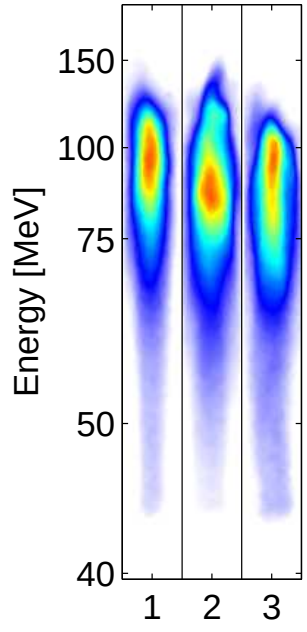
2 mm nozzle

Plateau density:
$4 \cdot 10^{18}\,\mathrm{cm}^{-3}$



400 μm tube

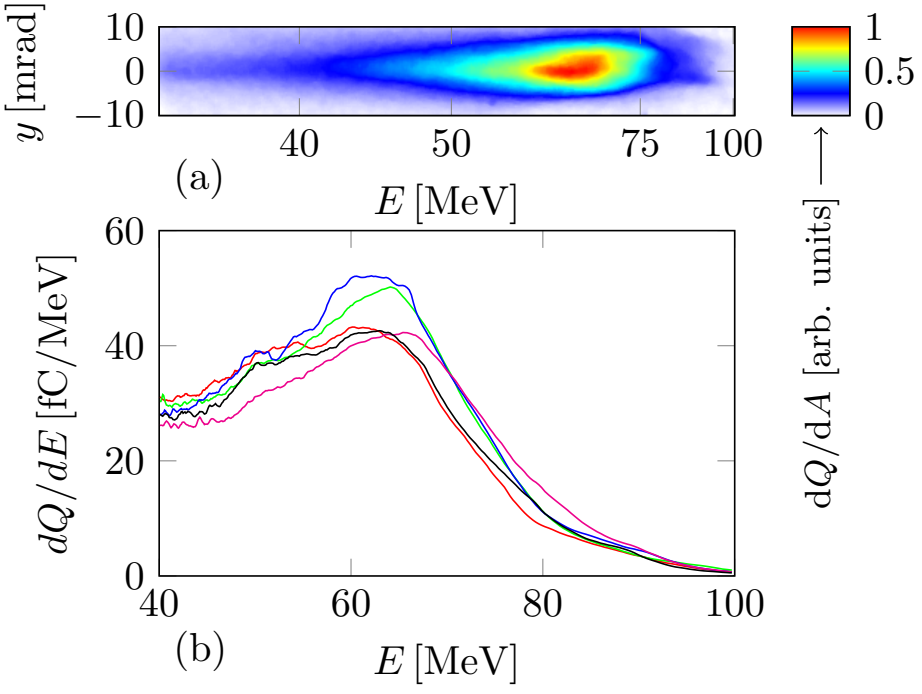
Peak density:
$8 \cdot 10^{18}\,\mathrm{cm}^{-3}$



Combined target

Peak density:
$12 \cdot 10^{18}\,\mathrm{cm}^{-3}$
Plateau density:
$4 \cdot 10^{18}\,\mathrm{cm}^{-3}$

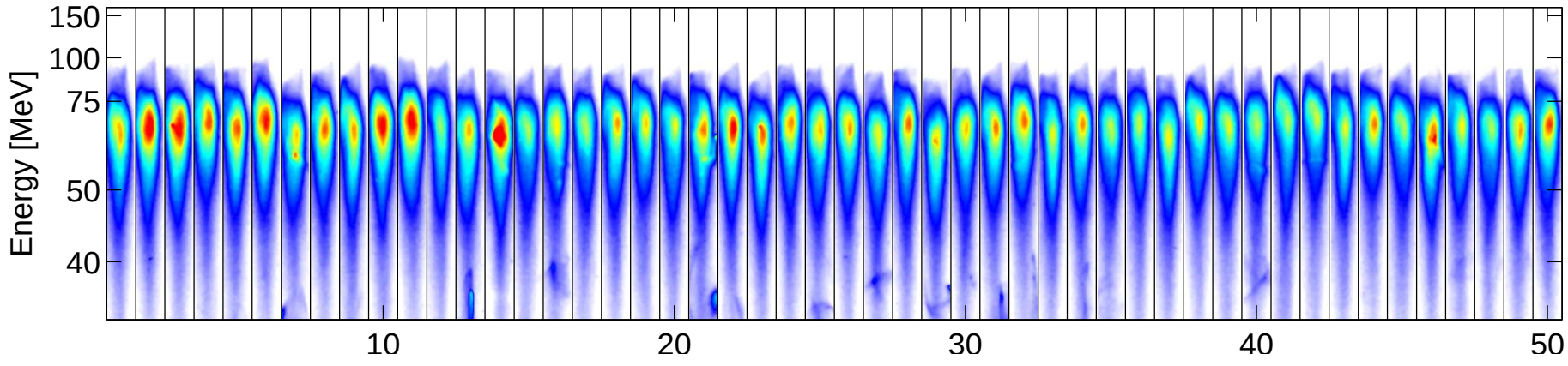
Stable beams of accelerated electrons



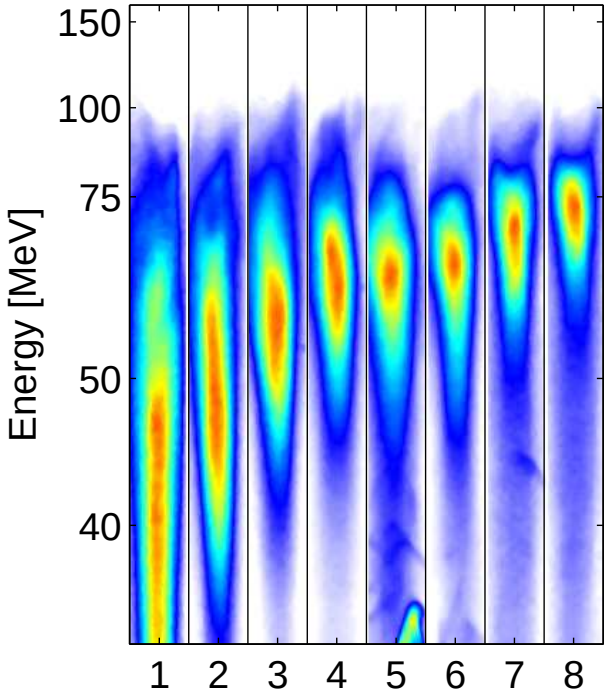
100 consecutive shots over 17 minutes

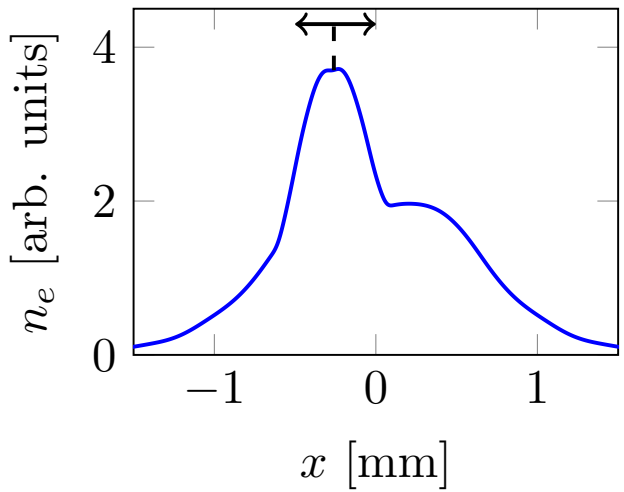
Peak density: $10 \cdot 10^{18}\,\mathrm{cm}^{-3}$
Plateau density: $3 \cdot 10^{18}\,\mathrm{cm}^{-3}$

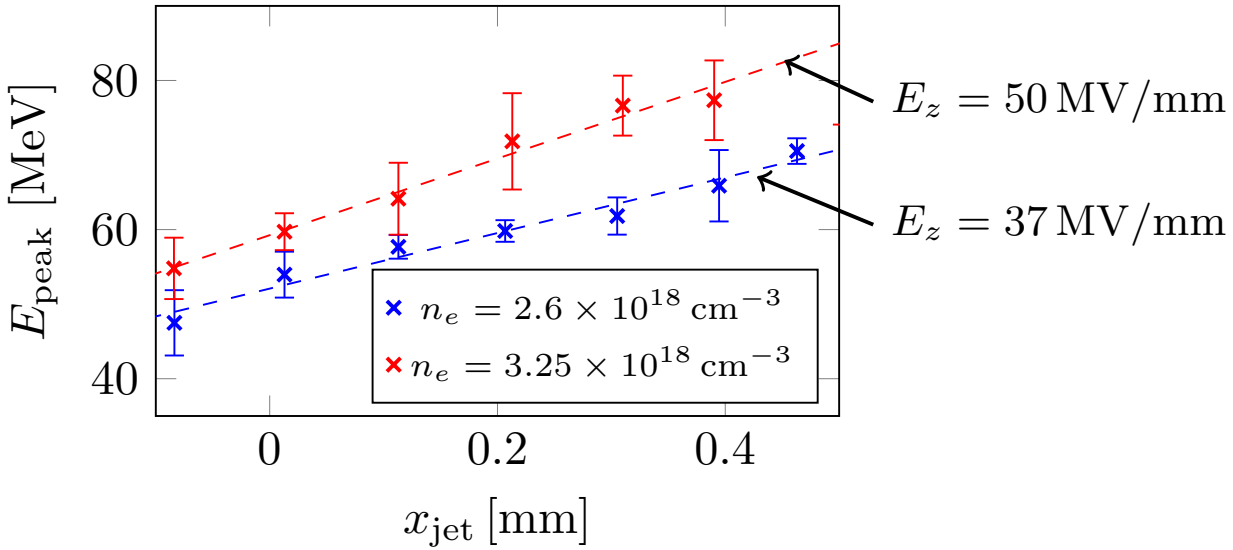
Average peak energy: $62\,\mathrm{MeV} \pm 5\%$
Average bunch charge: $1\,\mathrm{pC} \pm 13\%$



Tuning the acceleration length





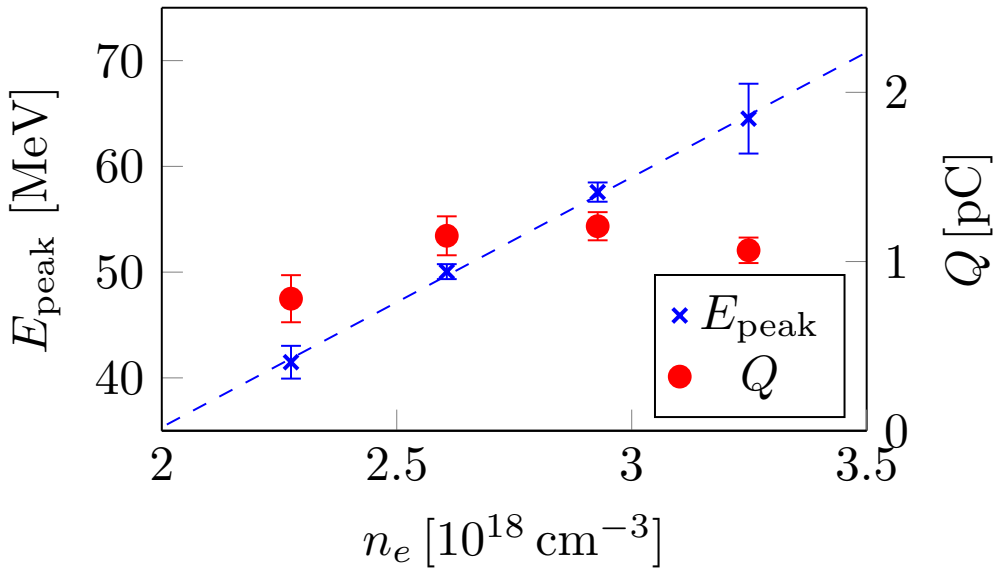


Peak density: $10 \cdot 10^{18}\,\text{cm}^{-3}$
Plateau density: $3 \cdot 10^{18}\,\text{cm}^{-3}$

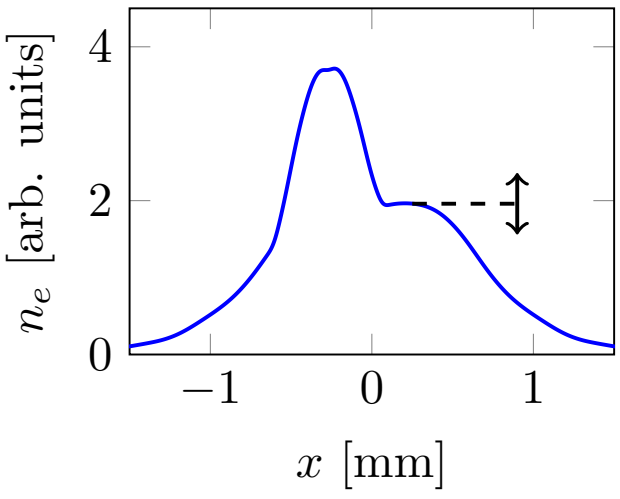
10 shots for each position

Extending the density plateau after the density ramp increases the electron bunch energy

Tuning the accelerating field

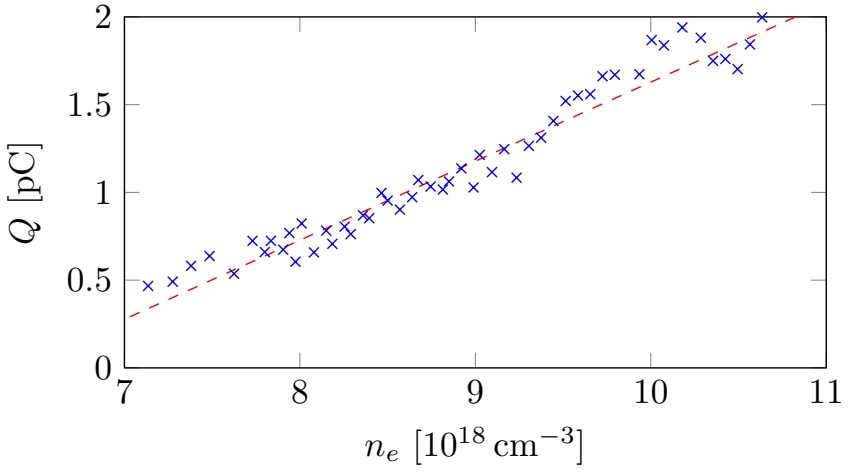


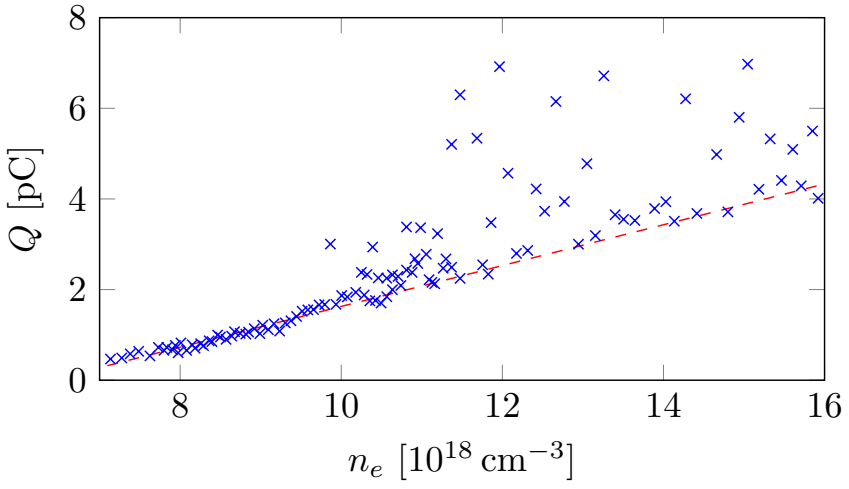
Peak density: $10 \cdot 10^{18}\,\mathrm{cm}^{-3}$
10 shots for each position



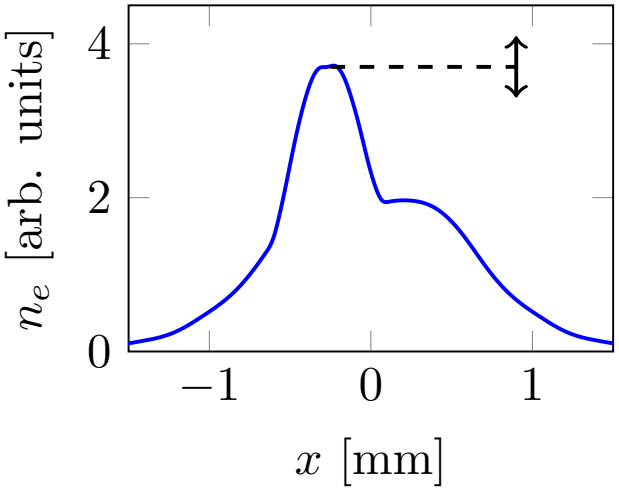
Increasing the plateau density
increases electron bunch energy

Tuning the electron bunch charge





Plateau density: $3 \cdot 10^{18}\,\mathrm{cm}^{-3}$



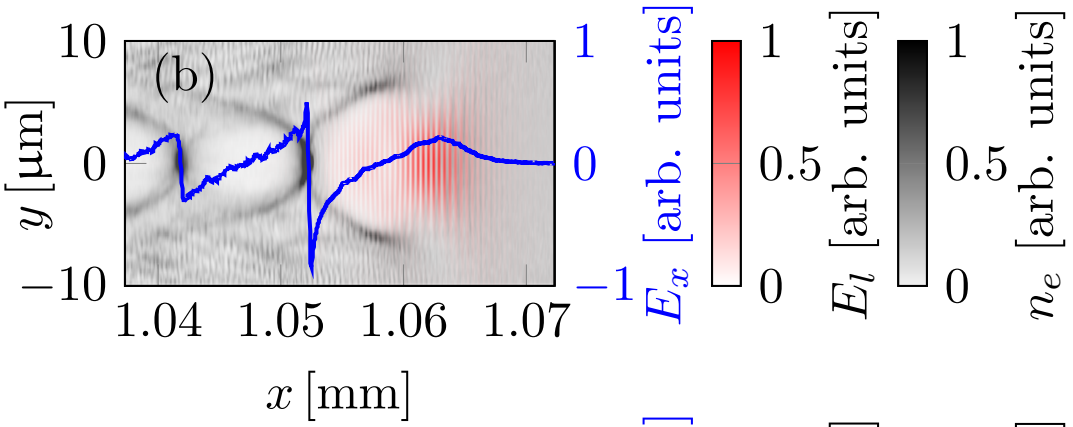
Increasing the peak density
increases the electron bunch charge

Self-trapping in density peak
above $\approx 11 \cdot 10^{18}\,\mathrm{cm}^{-3}$

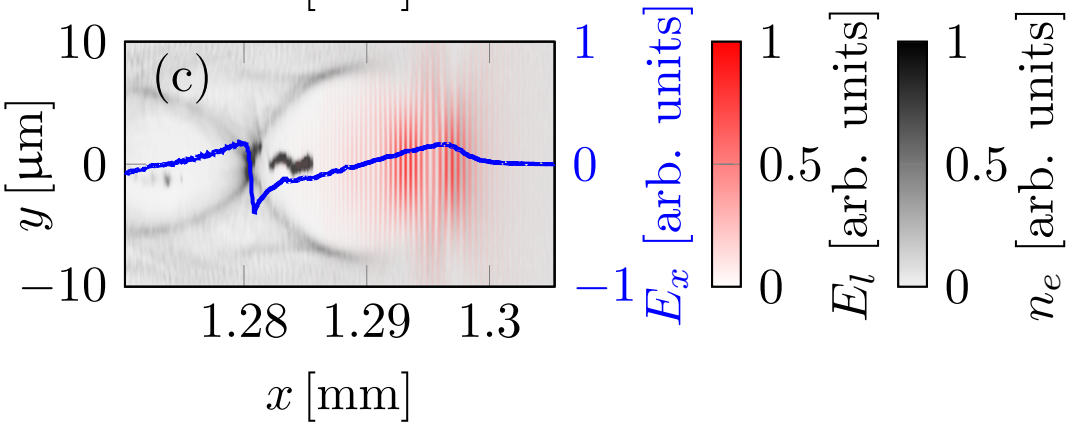
Simulations

Injection phase

Before density down ramp



After density down ramp

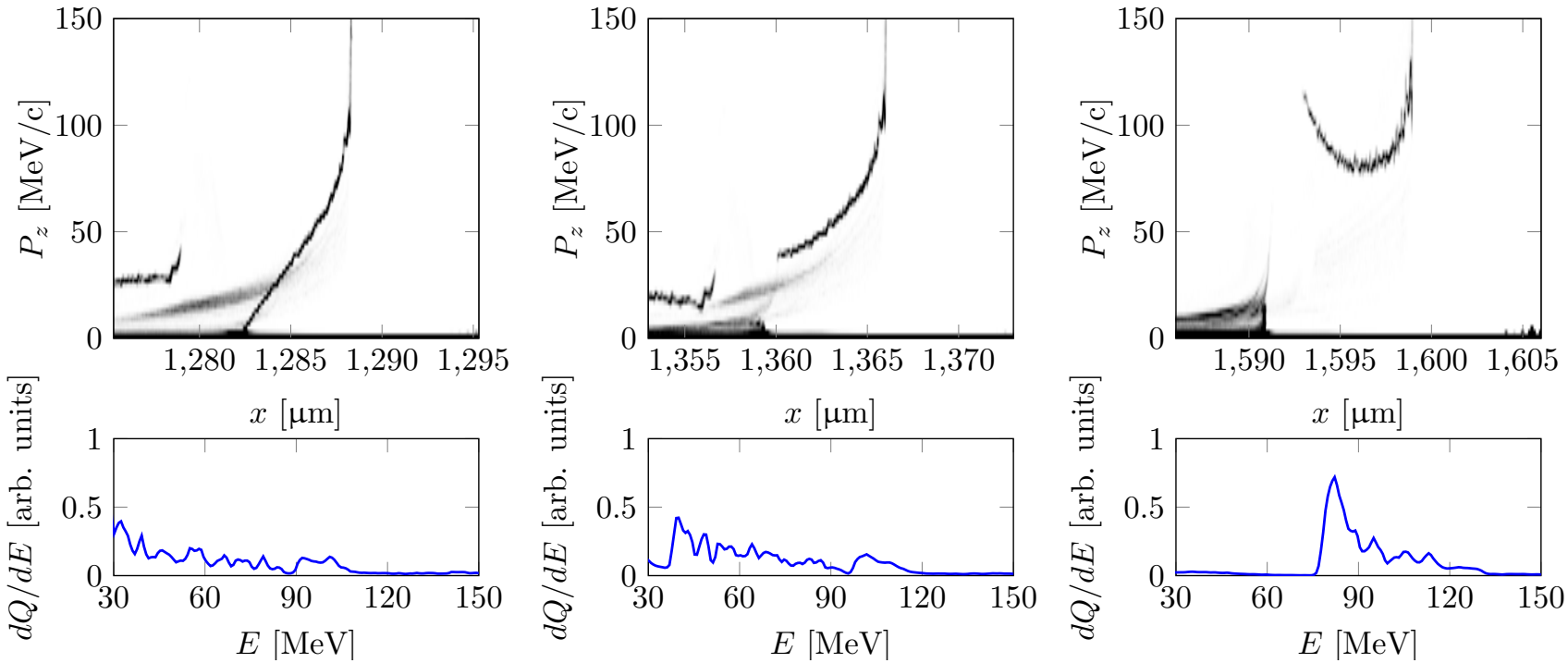


- Injection in down-ramp
- Initially large energy spread due to long ramp

Simulations using CALDER-CIRC, Lifschitz et al J. Comput. Phys. 228, 1803-1814 (2009)

Simulations

Acceleration phase



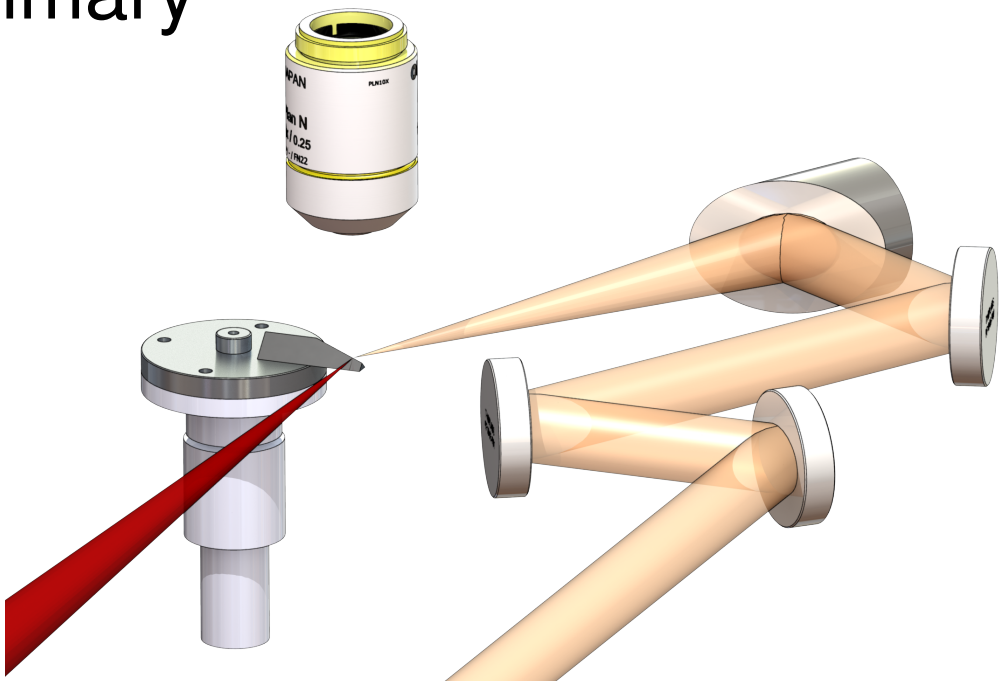
- Longitudinal extent allows for phase-space rotation
- Peaked spectrum after only $300\ \mu\mathrm{m}$

Simulations using CALDER-CIRC, Lifschitz et al J. Comput. Phys. 228, 1803-1814 (2009)

Summary

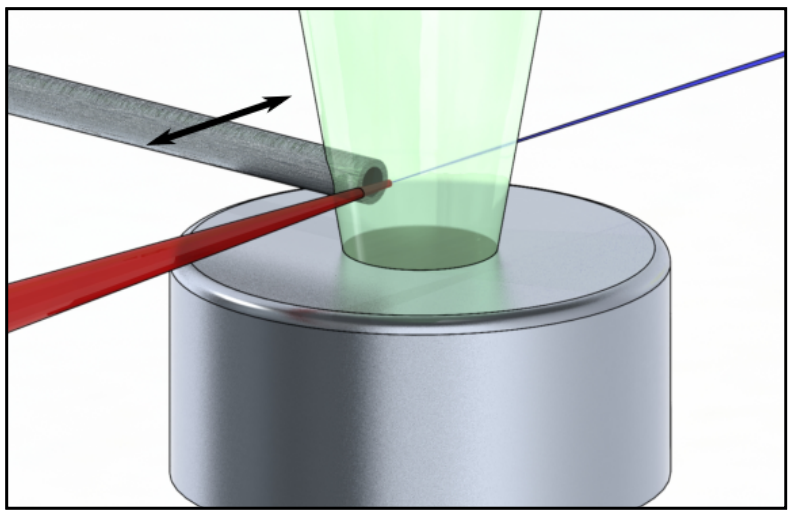
Colliding pulse injection

- Compact setup for CPI
- High quality beams generated
  - Low divergence
  - Small energy spread
- Controlled beam parameters
  - Energy by collision point
  - Charge by polarization



Density down-ramp injection

- Simple set-up
- Small fluctuations
- Controlled beam parameters
  - Energy by injection point
  - Energy by accelerating field
  - Charge by gradient



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