Control of electron injection and acceleration in a laser-plasma accelerator

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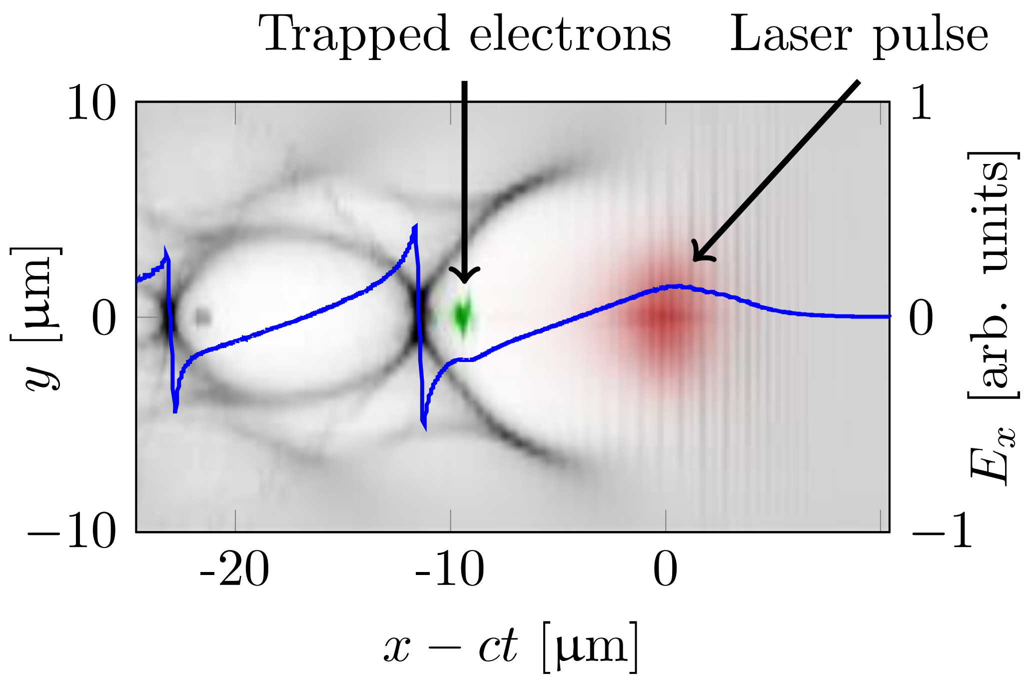
Laser wakefield acceleration



+ High accelerating field (~100 GV/m)
+ Intrinsically short electron bunches (~1 fs)

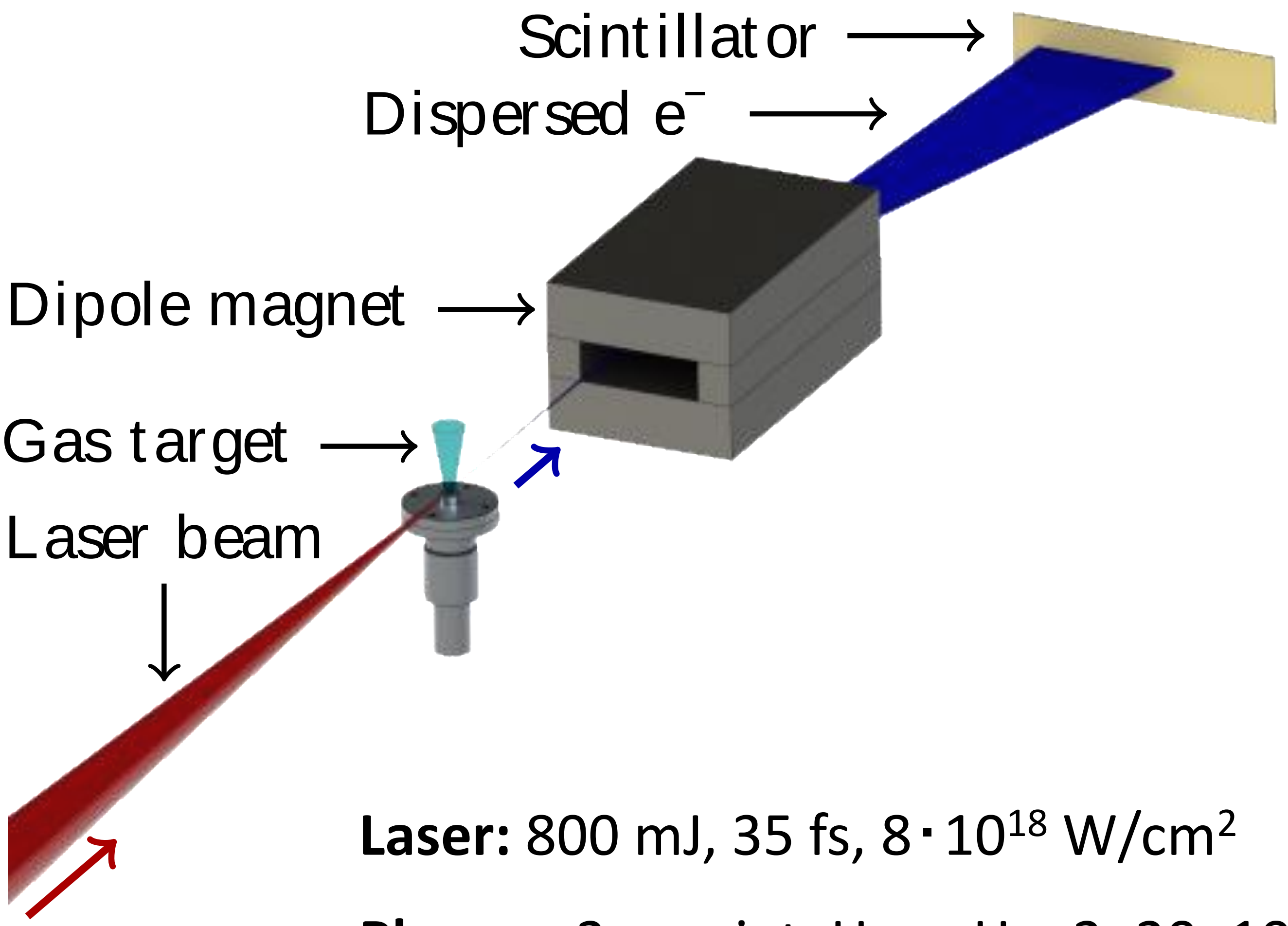
– Hard to control (charge, energy, divergence, etc.)
– Large fluctuations

Surfing the wake wave

Three fundamental methods for controlled injection

- Drop electrons at the correct place -> ionization injection
- Slow down the wakefield -> density gradient injection
- Speed up the electrons -> colliding pulse injection

Typical experimental setup

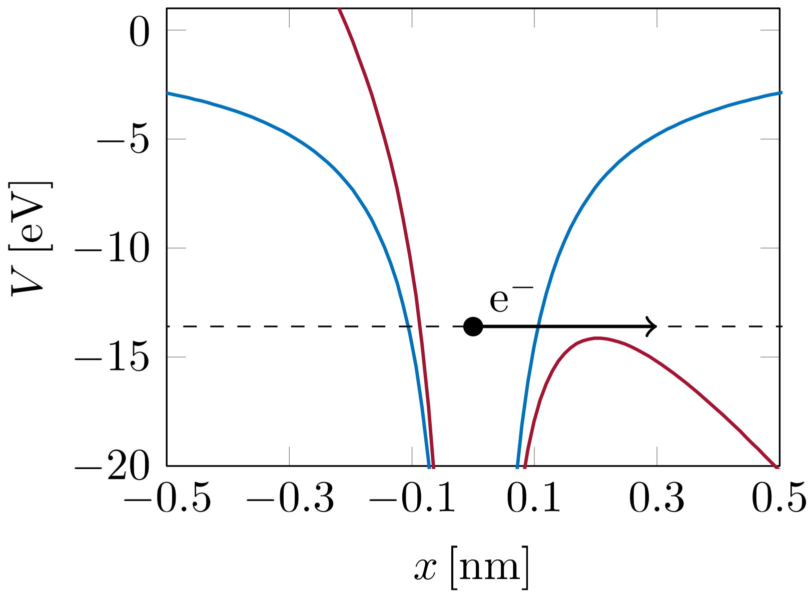


Laser: 800 mJ, 35 fs, $8 \cdot 10^{18}$ W/cm^2

Plasma: 2 mm jet, H_2 or He, $2–20 \cdot 10^{18}$ e-/cm^3

Ionization by barrier suppression

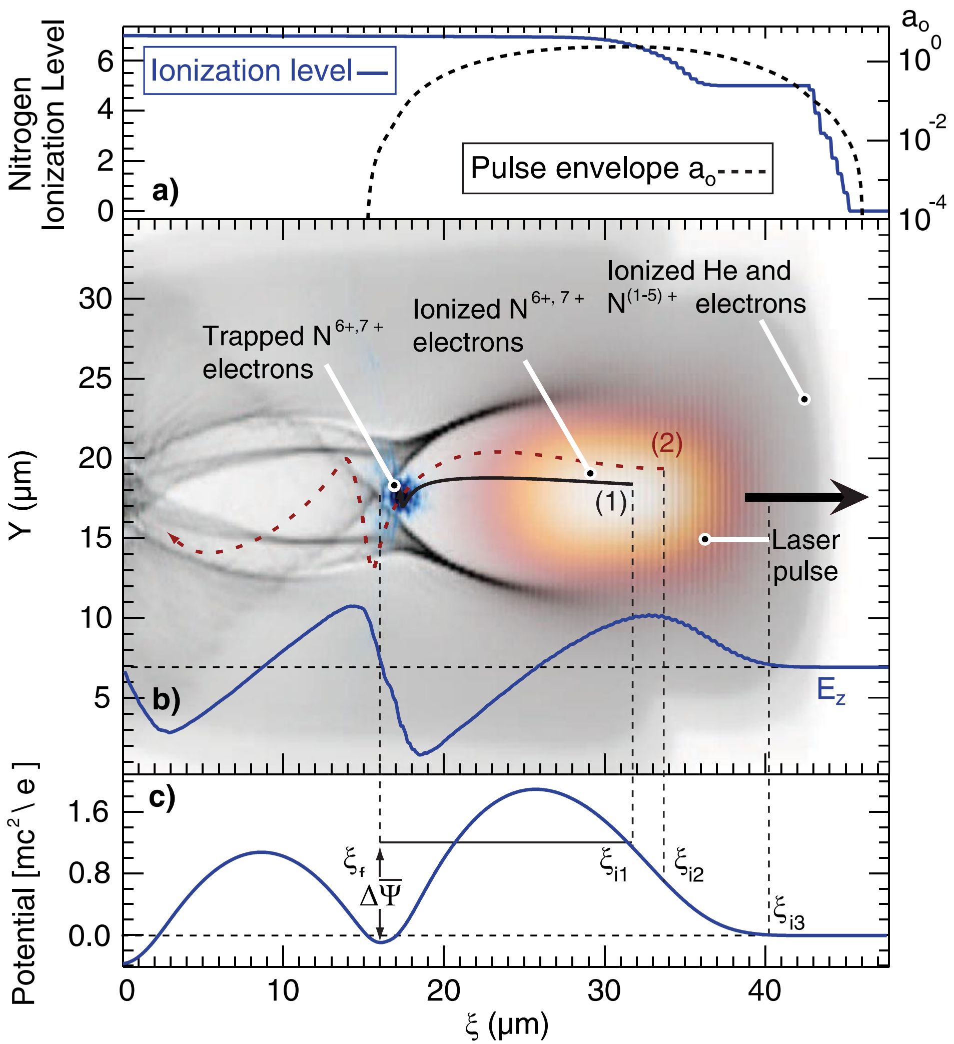
Atomic potential with laser field



$$I\,[\mathrm{W/cm^2}] = 4 \times 10^9 E_i^{\,4}[\mathrm{eV}] \,/\, Z^2$$

Ion	**E_{Ion} [eV]**	**I_{App} [W/cm²]**
H^+	13.6	1.4×10^{14}
He^+	24.6	1.5×10^{15}
He^{2+}	54.4	8.8×10^{15}
N^+	14.5	1.8×10^{14}
N^{2+}	29.6	7.7×10^{14}
N^{3+}	47.4	2.3×10^{15}
N^{4+}	77.5	9.0×10^{15}
N^{5+}	97.9	1.5×10^{16}
N^{6+}	552.1	1.0×10^{19}
N^{7+}	667.0	1.6×10^{19}

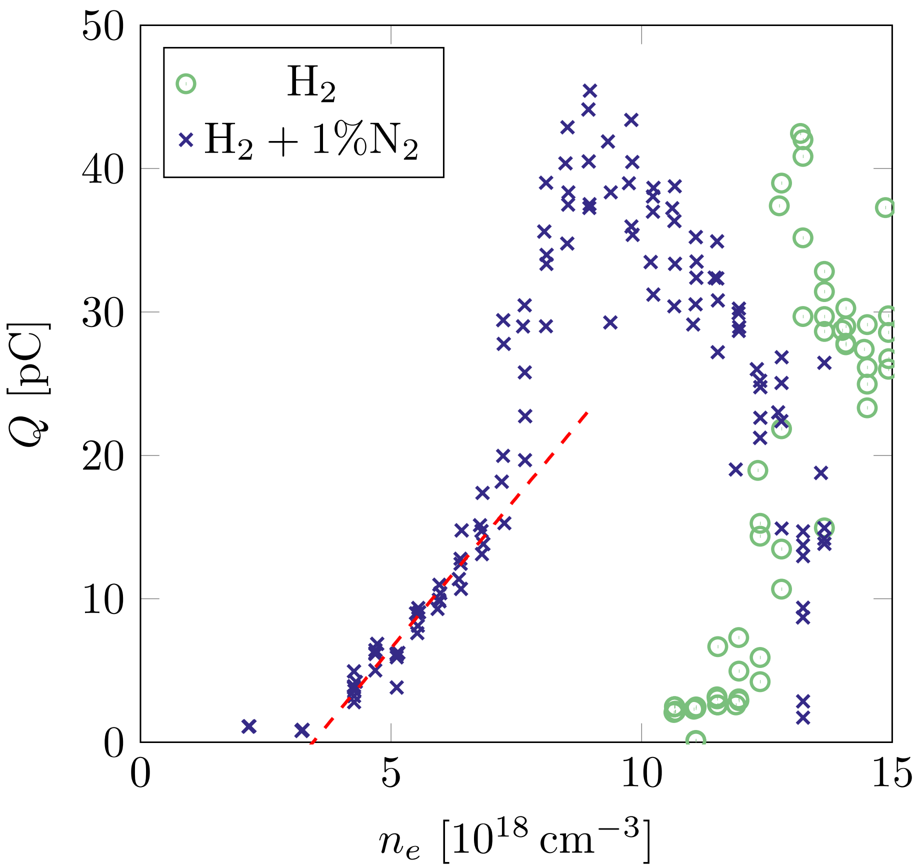
Ionization injection



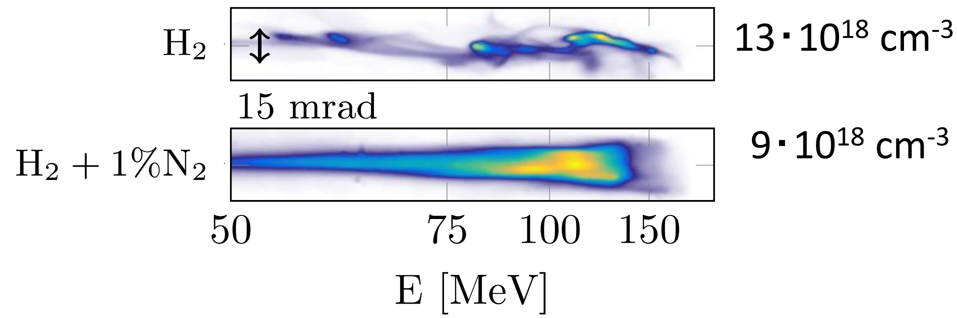
- Background plasma created by front edge of the laser pulse
- Core e- are ionized close to laser peak and are born inside the wake itself
- If they are born in the right phase, they can be trapped

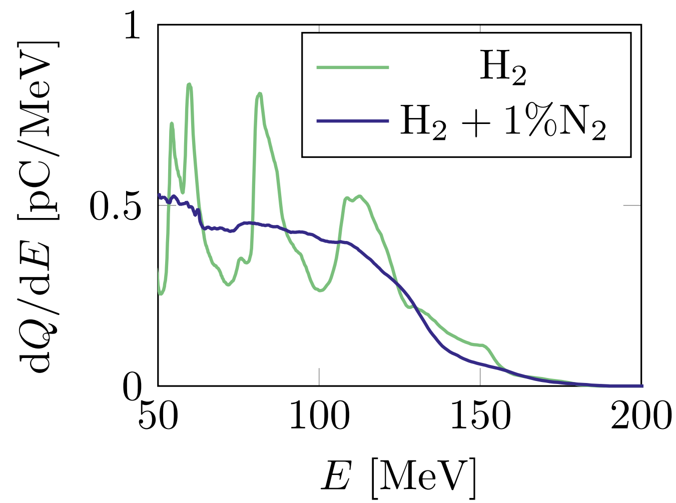
Illustration: A. Pak et al., Phys. Rev. Lett. 104, 025003 (2010)

Density dependence



Typical beams with Q ≈ 40 pC





Mixture H2+1%N2

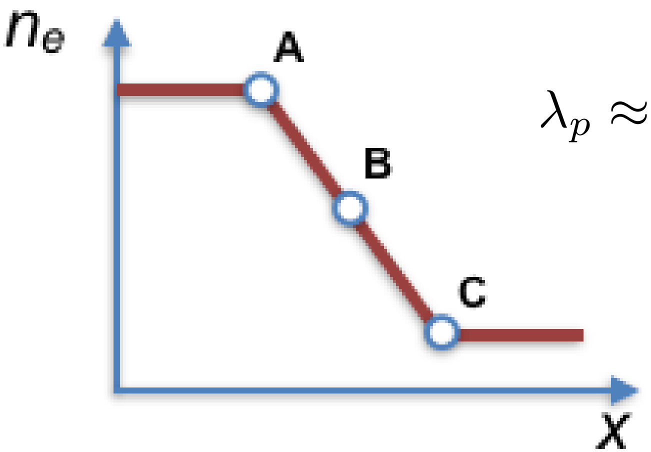
- Threshold ≈ $3 \cdot 10^{18}$ cm^{-3}
- Broad energy spectrum
- Stable

Pure H2

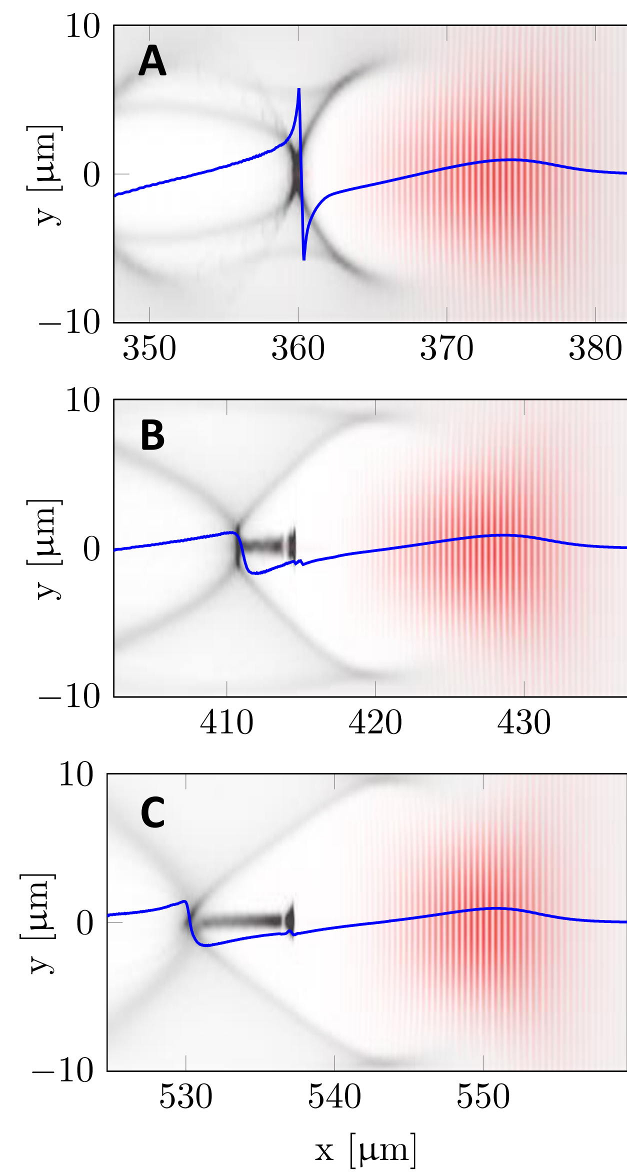
- Threshold ≈ $1 \cdot 10^{19}$ cm^{-3}
- Narrow spectral features
- Fluctuations

Hansson *et al*, Plasma Phys Control Fusion 58, 055009 (2016)

Density down-ramp injection



$$\lambda_p \approx \frac{2\pi c}{q_e}\sqrt{\frac{\epsilon_0 m_e}{n_e}}$$



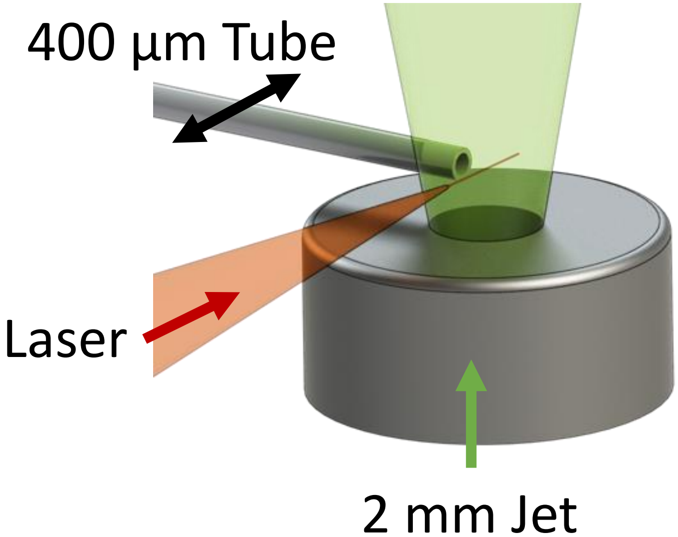
In the down-ramp, λ_p increases

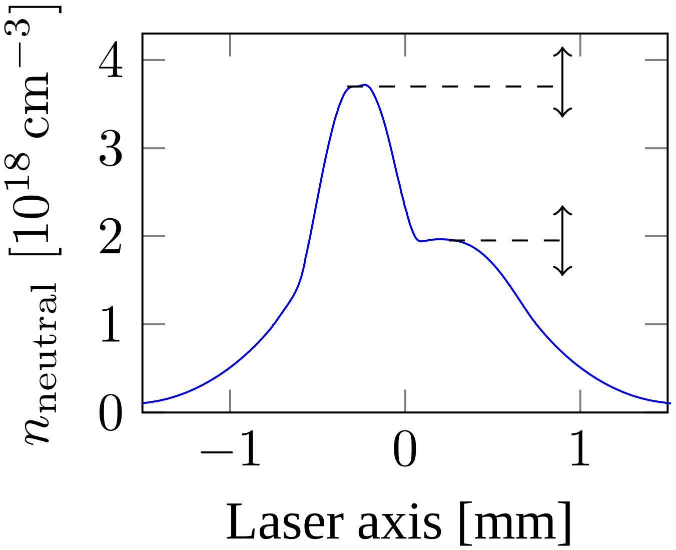
- Bubble elongates
- Effective slow-down of the back of the bubble
- Effective decrease of the phase velocity

➢ Localized trapping
➢ Decreased threshold for self-injection

Simulation by H Ekerfelt using Calder-Circ

Combined gas target

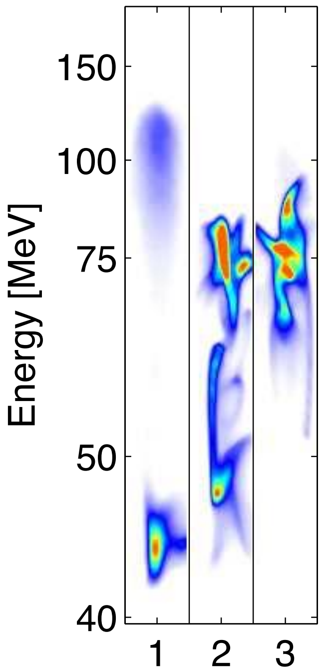




- Two sources of gas — two regions with different density
- Downward gradient length ≈ 230 µm ≈ 10λ_p
- Controlled: Gradient position
  Peak density
  Plateau density

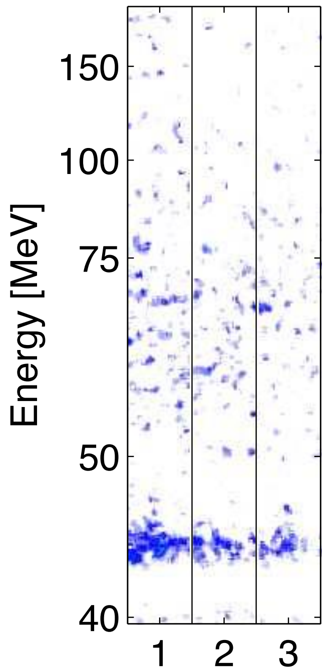
Hansson *et al*, Phys Rev STAB 18, 071303 (2015)

First results



2 mm jet

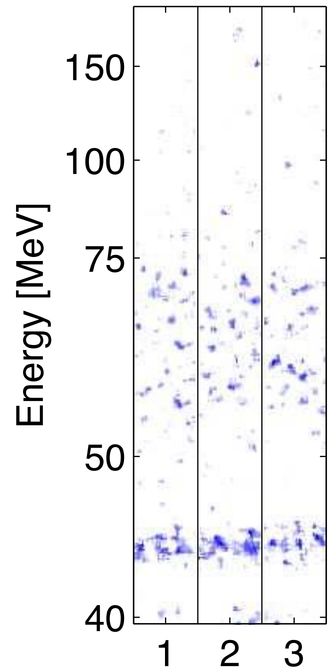
$13 \cdot 10^{18}$ e^{-}/cm^{3}



2 mm jet

$4 \cdot 10^{18}$ e^{-}/cm^{3}

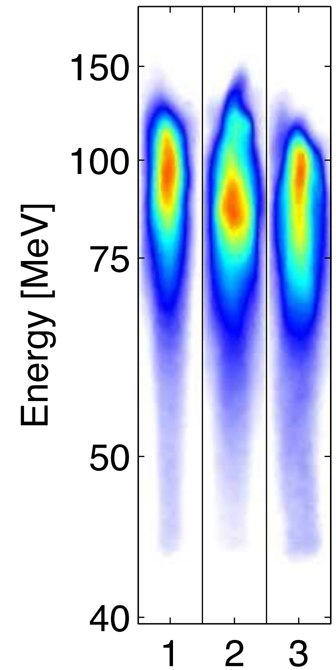
(no e- above 40 MeV)



400 µm tube

$8 \cdot 10^{18}$ e^{-}/cm^{3}

(no e- above 40 MeV)



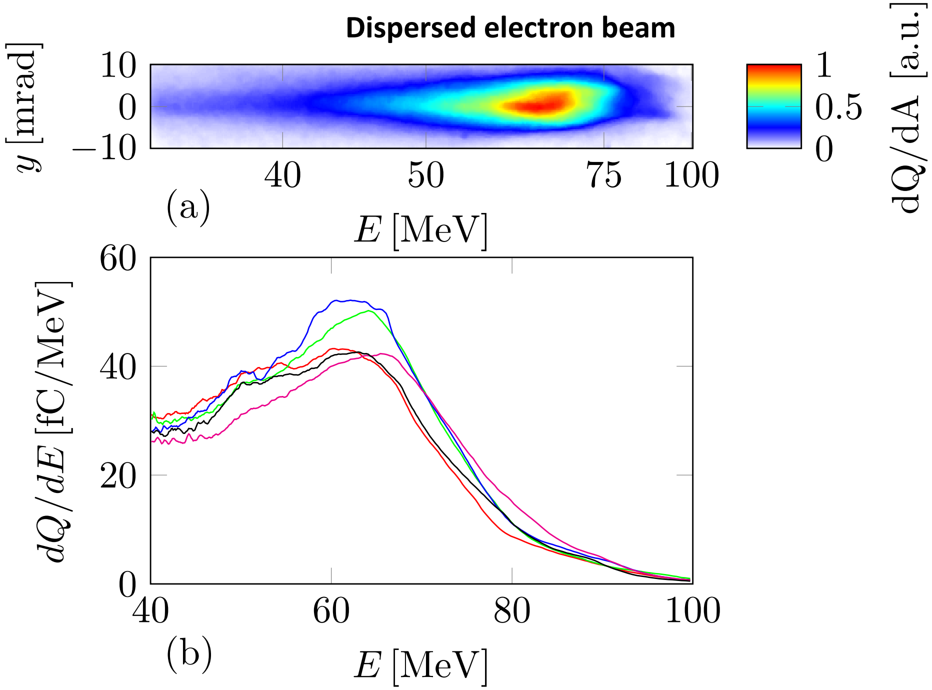
Combined target

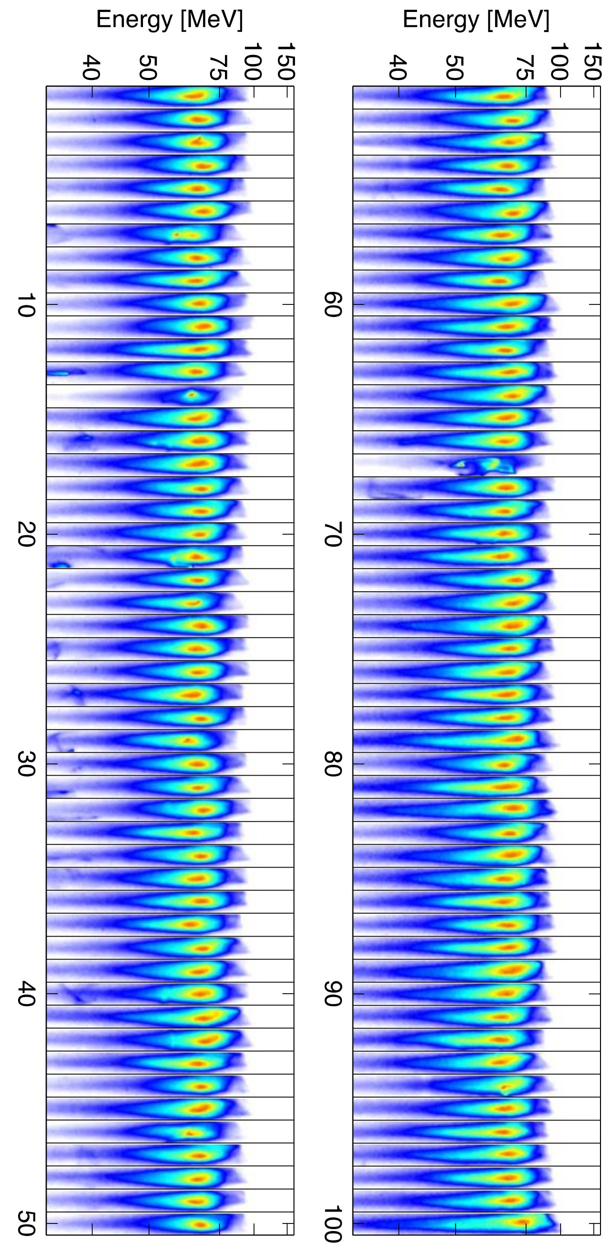
$8 \cdot 10^{18}$ e^{-}/cm^{3}

$4 \cdot 10^{18}$ e^{-}/cm^{3}

Hansson *et al*, Phys Rev STAB 18, 071303 (2015)

Stable electron beams





Average peak energy: 62 MeV ± 5%
Average bunch charge: 2 pC ± 13%

100 consecutive shots

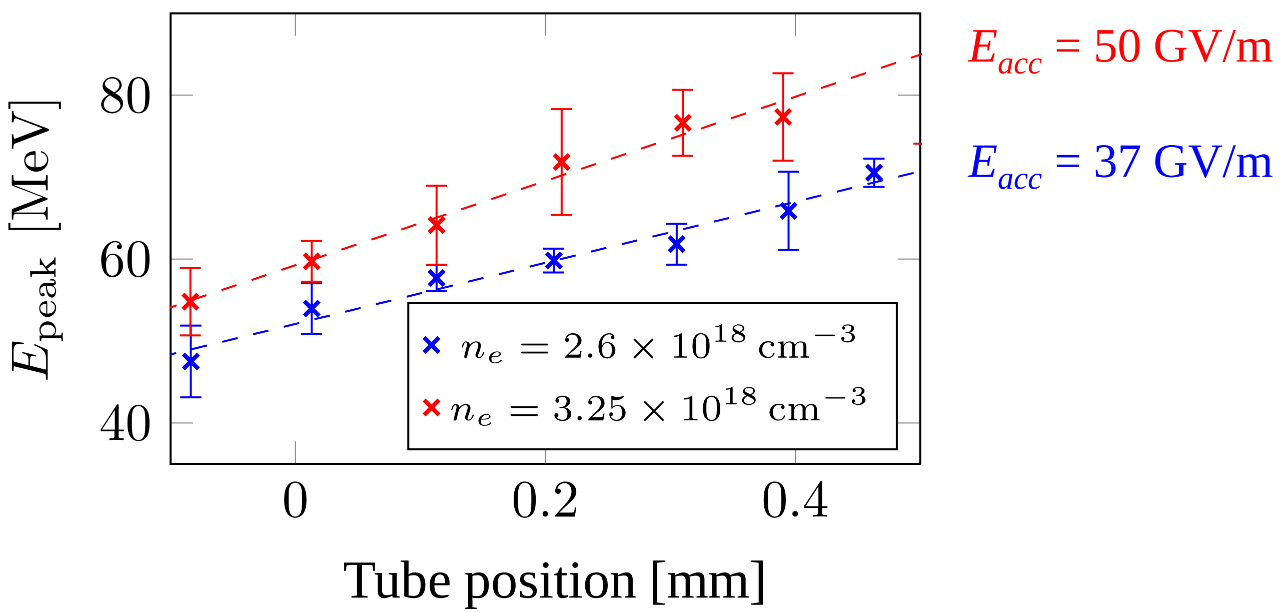
17 minutes

Peak density: 10×10^{18} cm^{-3}

Plateau density: 3×10^{18} cm^{-3}

Hansson *et al*, Phys Rev STAB 18, 071303 (2015)

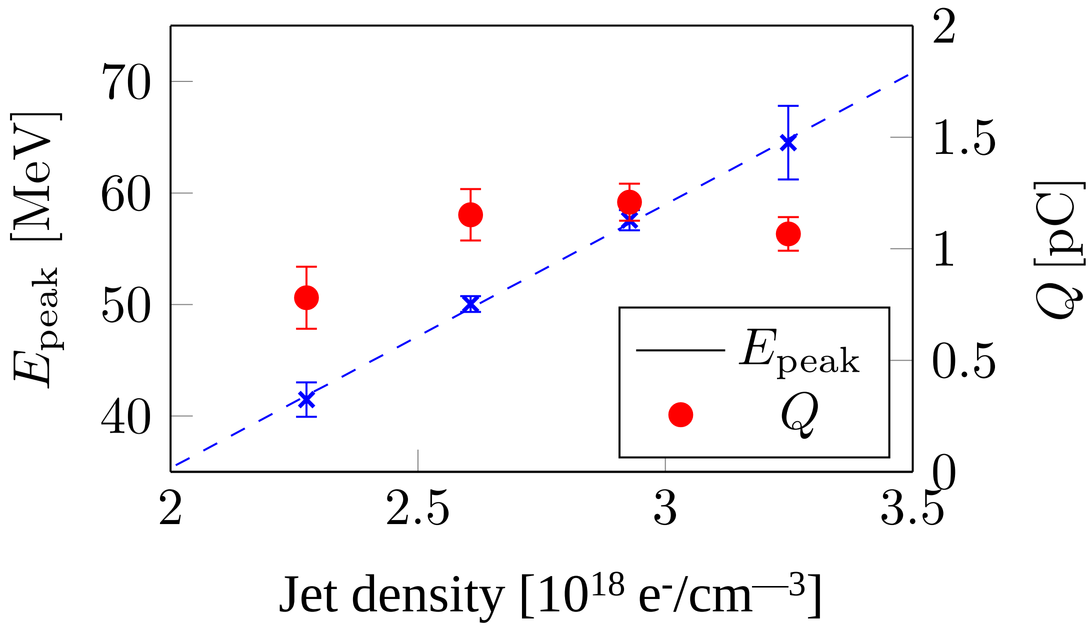
Tuning peak energy and charge



Acceleration length	✓ Tuned by tube position
Acceleration field	✓ Tuned by gas density in jet
Charge	✓ Tuned by gas density in tube

Hansson *et al*, Phys Rev STAB 18, 071303 (2015)

Tuning peak energy and charge



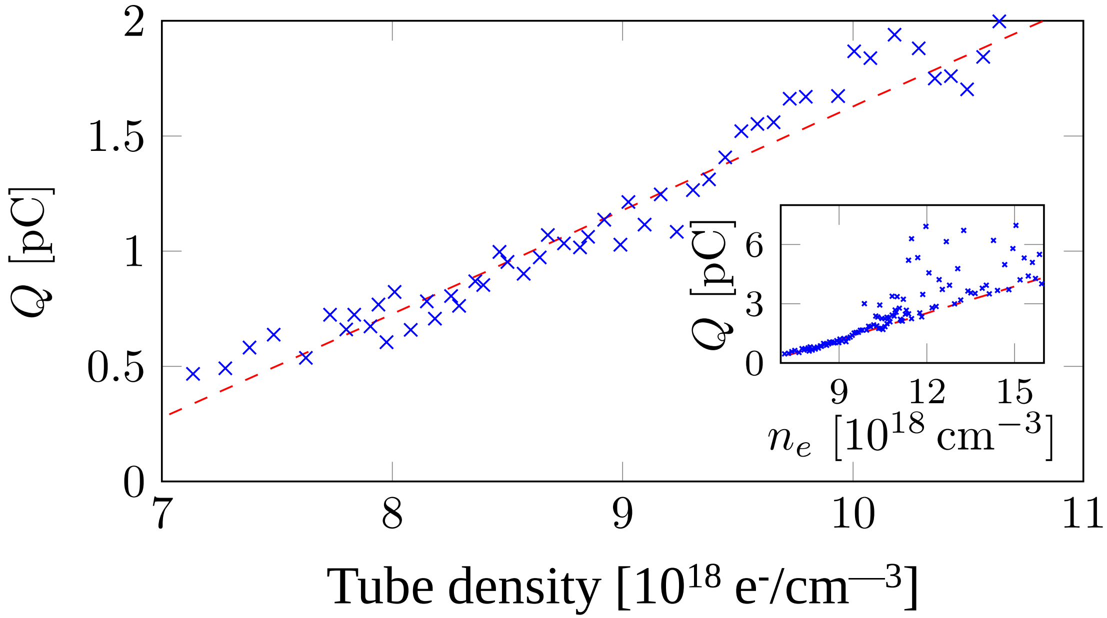
Acceleration length ✓ Tuned by tube position

Acceleration field ✓ Tuned by gas density in jet

Charge ✓ Tuned by gas density in tube

Hansson *et al*, Phys Rev STAB 18, 071303 (2015)

Tuning peak energy and charge



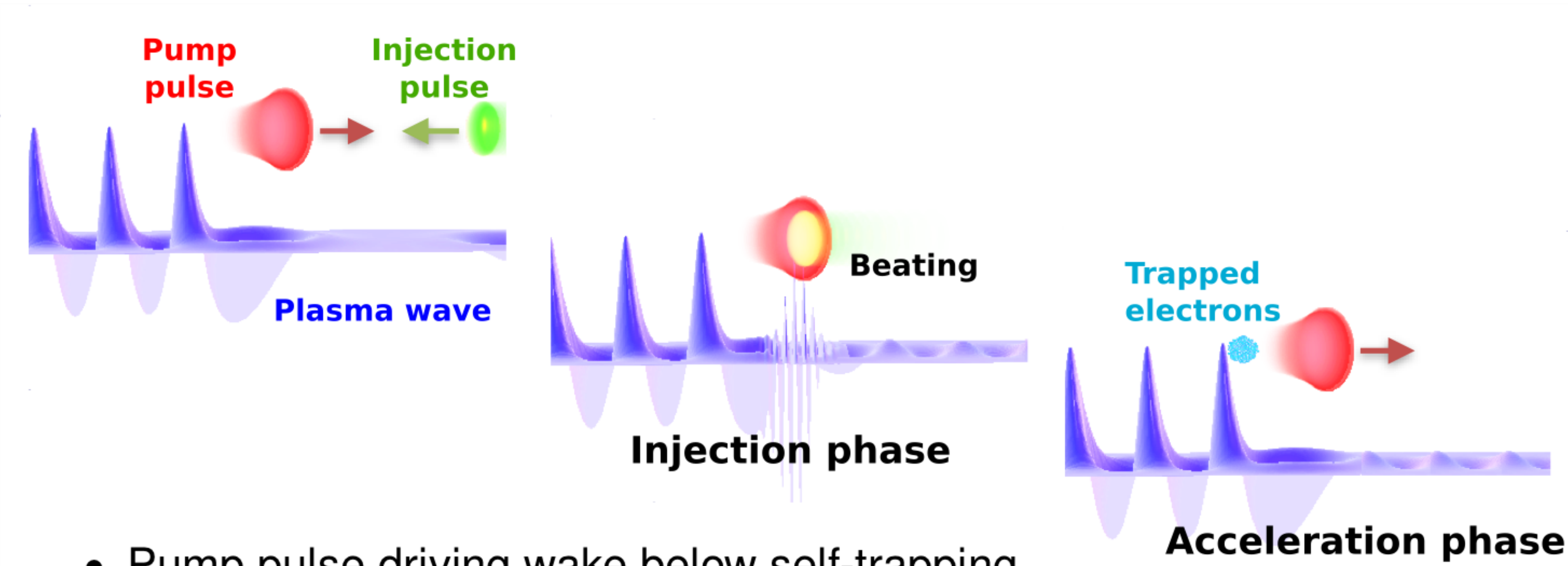
Acceleration length ✓ Tuned by tube position

Acceleration field ✓ Tuned by gas density in jet

Charge ✓ Tuned by gas density in tube

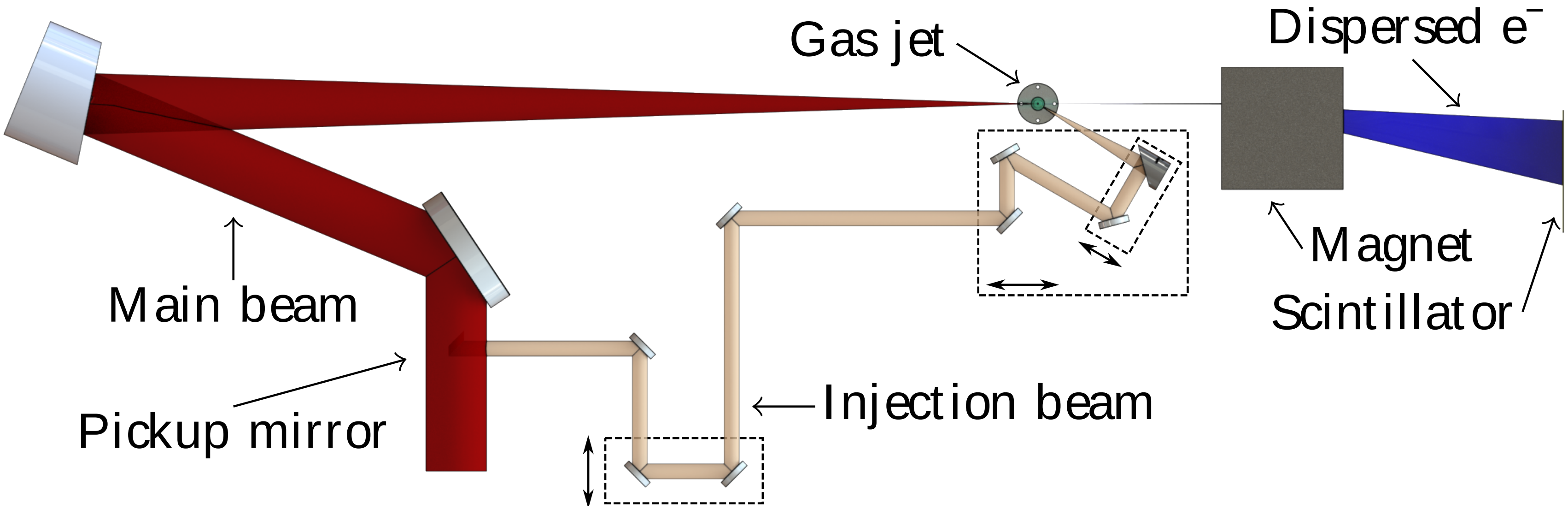
Hansson *et al*, Phys Rev STAB 18, 071303 (2015)

Colliding Pulse Injection



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

Colliding pulses in a gas jet

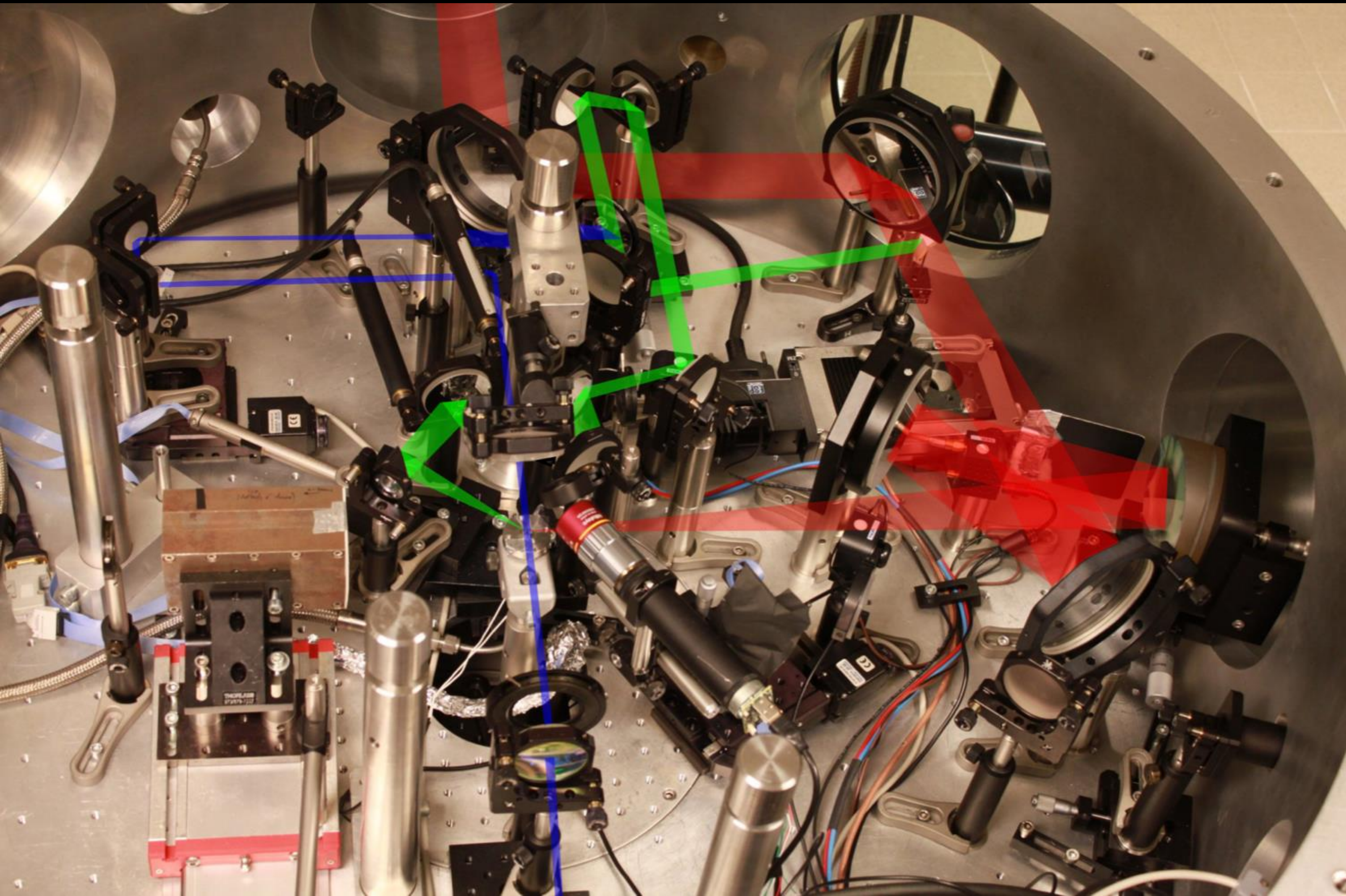


Pump laser: 500 mJ, 40 fs, 3×10^{18} W/cm^2

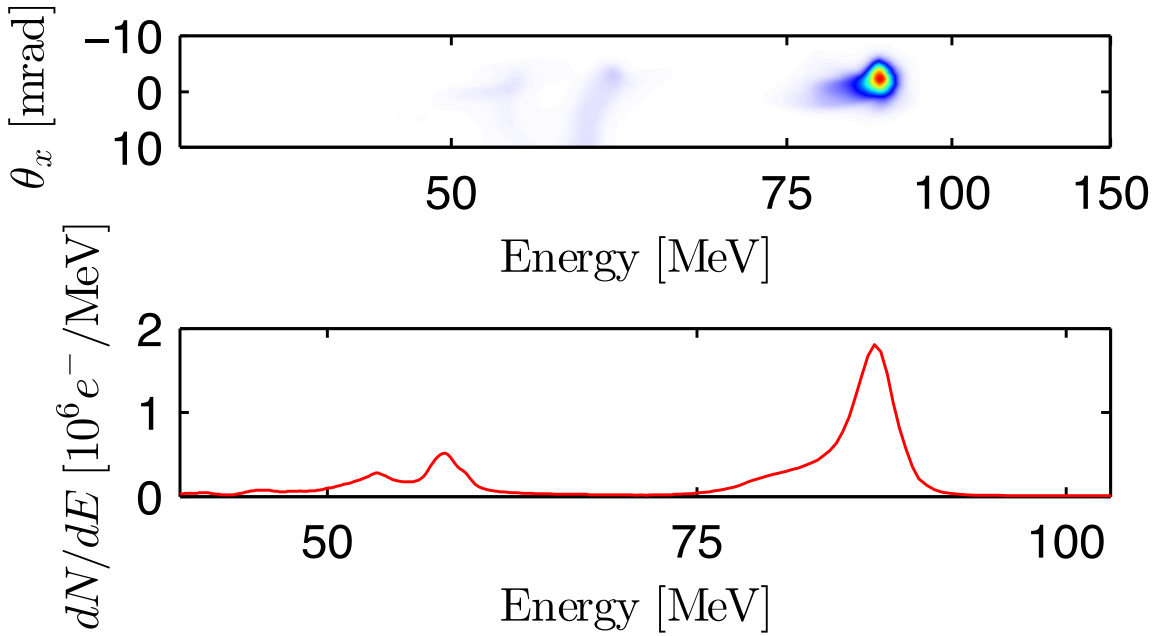
Injection laser: 40 mJ, 40 fs, 1×10^{18} W/cm^2

Hansson *et al*, NIMA 829, 99-103 (2016)

Colliding pulses in a gas jet



Beam quality



E_{peak} = 86 MeV

Q_{peak} = 2 pC

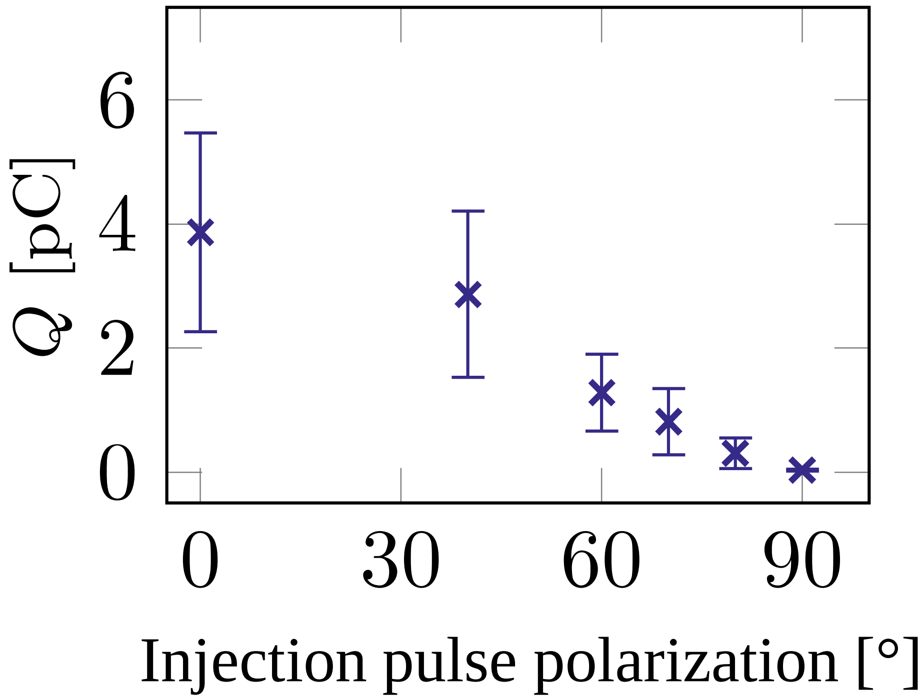
$\Delta\theta$ = 4 mrad

$\Delta E/E$ = 3.5%

Hansson *et al*, NIMA 829, 99-103 (2016)

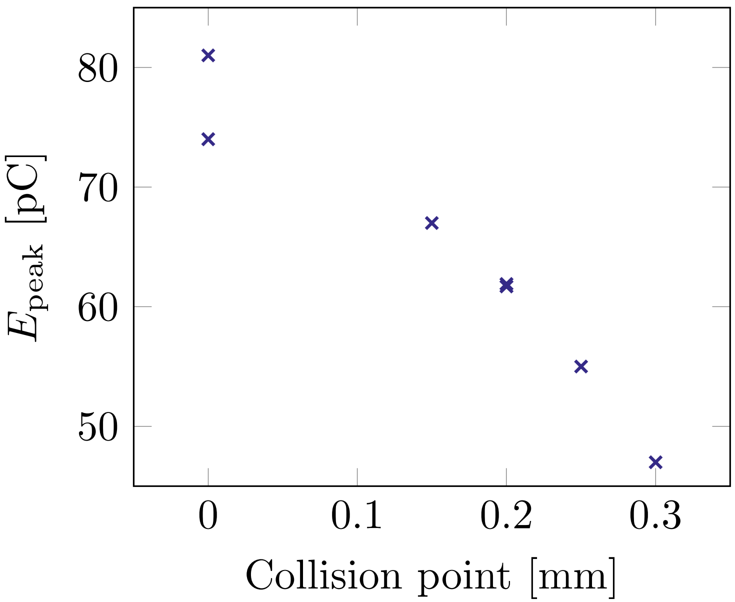
Polarization dependence

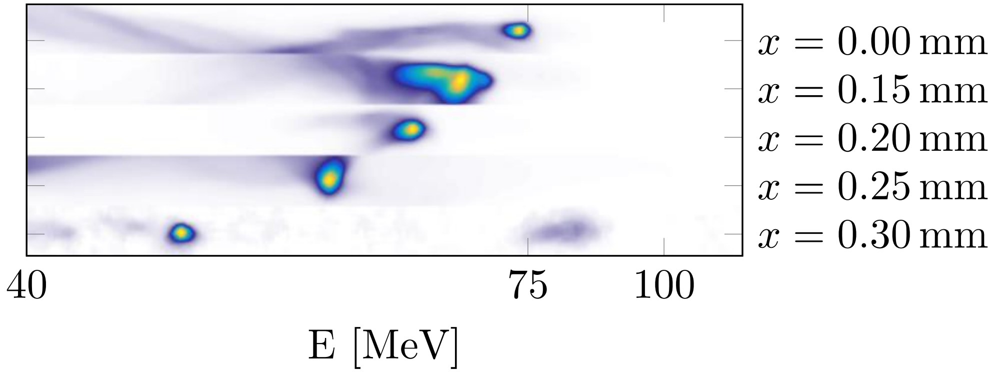
Charge can be controlled by the polarization



Hansson *et al*, NIMA 829, 99-103 (2016)

Tunable energy





$x = 0\,\text{mm}$ - 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 $150\,\text{MV/mm}$

Hansson *et al*, NIMA 829, 99-103 (2016)

Summary of contribution

Controlled injection and acceleration in laser-plasma accelerators using

- Two gas jets (density down-ramp injection)
- Two laser beams (colliding pulse injection)
- Two types of gas (ionization injection)

PhD Thesis (partly funded through EuCARD2)

M Hansson, “Controlled trapping in laser wakefield accelerators”, 2016

Articles (with EuCARD2 acknowledgement)

1. Svensson *et al*, Phys Rev AB **19**, 051301 (2016)
2. Hansson *et al*, Plasma Phys Control Fusion **58**, 055009 (2016)
3. Hansson *et al*, Nucl Instr Meth Phys Res A **829**, 99-103 (2016)
4. Audet *et al*, Phys Plasmas **23**, 023110 (2016)
5. Hansson *et al,* Phys Rev STAB **18**, 071303 (2015)
6. Hansson *et al*, Phys Rev STAB **17**, 031303 (2014)
7. Desforges *et al*, Nucl Instr Meth Phys Res A **740**, 54-59 (2014)
8. Desforges *et al*, Phys Plasmas **21**, 120703 (2014)

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Injection schemes “toolbox”

Injection mech.	Charge	Energy range	ΔE/E	Divergence	Tuneability	Stability	Simplicity
Self-injection	10-200 pC	50-200 MeV	10 - 100 %	5-10 mrad	– –	– –	+ +
Ionization	5-50 pC	50-200 MeV	100 %	10 mrad	+	+	+ +
Down-ramp	1-10 pC	40-100 MeV	50 %	10 mrad	+ + +	+ + +	+
Colliding pulses	1-10 pC	40 -100 MeV	3 %	3 mrad	+ + +	+	–
Shock-front*	1-10 pC	40-100 MeV	5 %	5 mrad	+ +	+	+
Shock + ionization*	1-10 pC	80-150 MeV	7 %	4 mrad	+ +	+ +	+

* Joint work with LOA (Thaury et al, Sci Rep **5**, 16310, 2015)

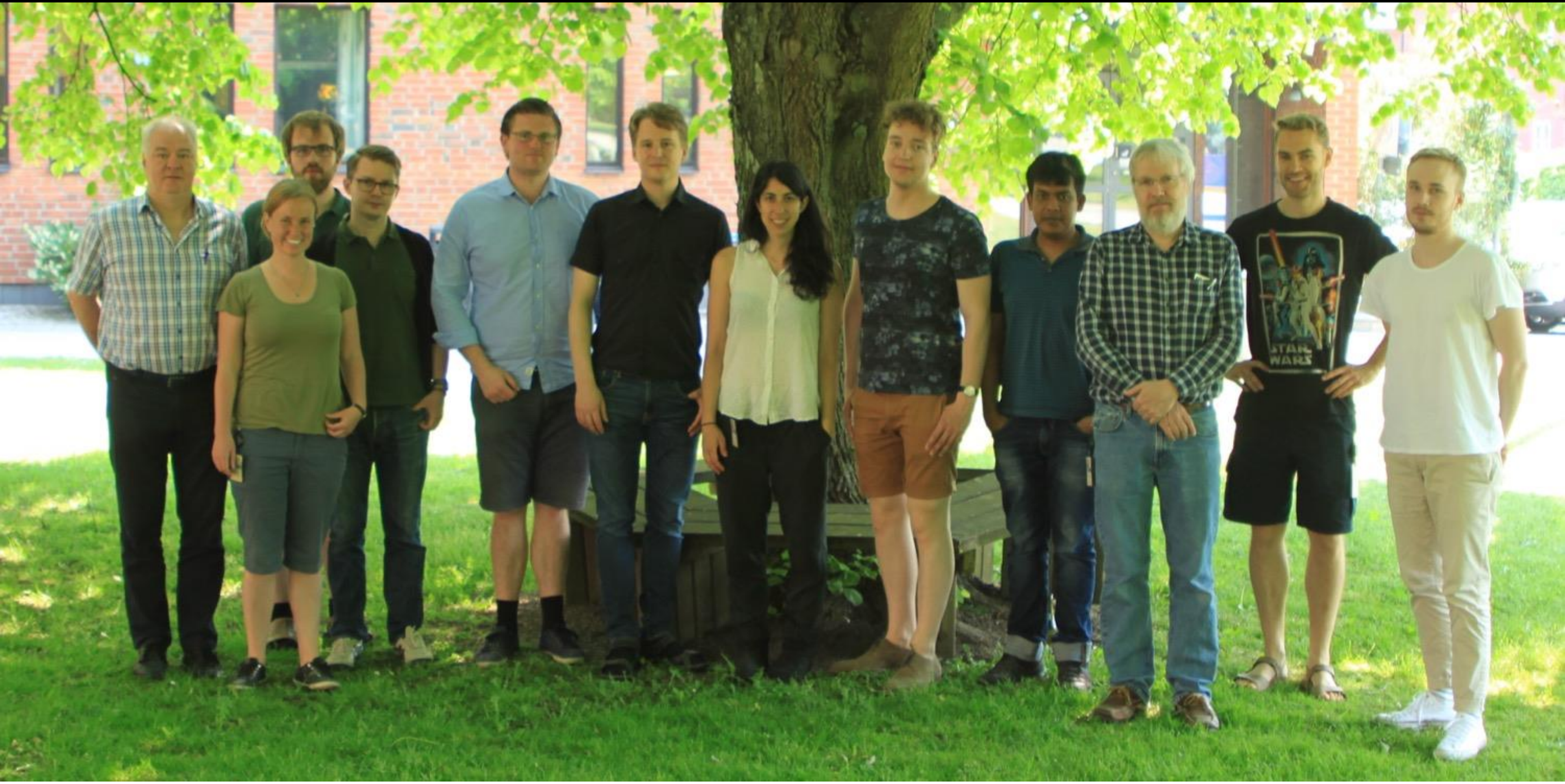
Planned contribution in ARIES

JRA : Increase the charge from the laser plasma accelerator

TNA : User access to laser, x-ray and electron beams for

- Time-resolved studies using betatron X-rays
- Studies of ultrashort pulses of electrons
- High energy electron radiotherapy
- ...

Acknowledgement



LOA: V Malka *et al.*

CEA: X Davoine

Imperial College: SPD Mangles *et al.*

ELI-Beamlines: K Falk, M, Schmid

LPGP: B Cros *et al.*

MAX IV: S Werin, F Curbis, S Thorin

Chalmers: M Marklund, A Gonoskov, T Fulöp et al.