Electron rephasing in laser-wakefield accelerators

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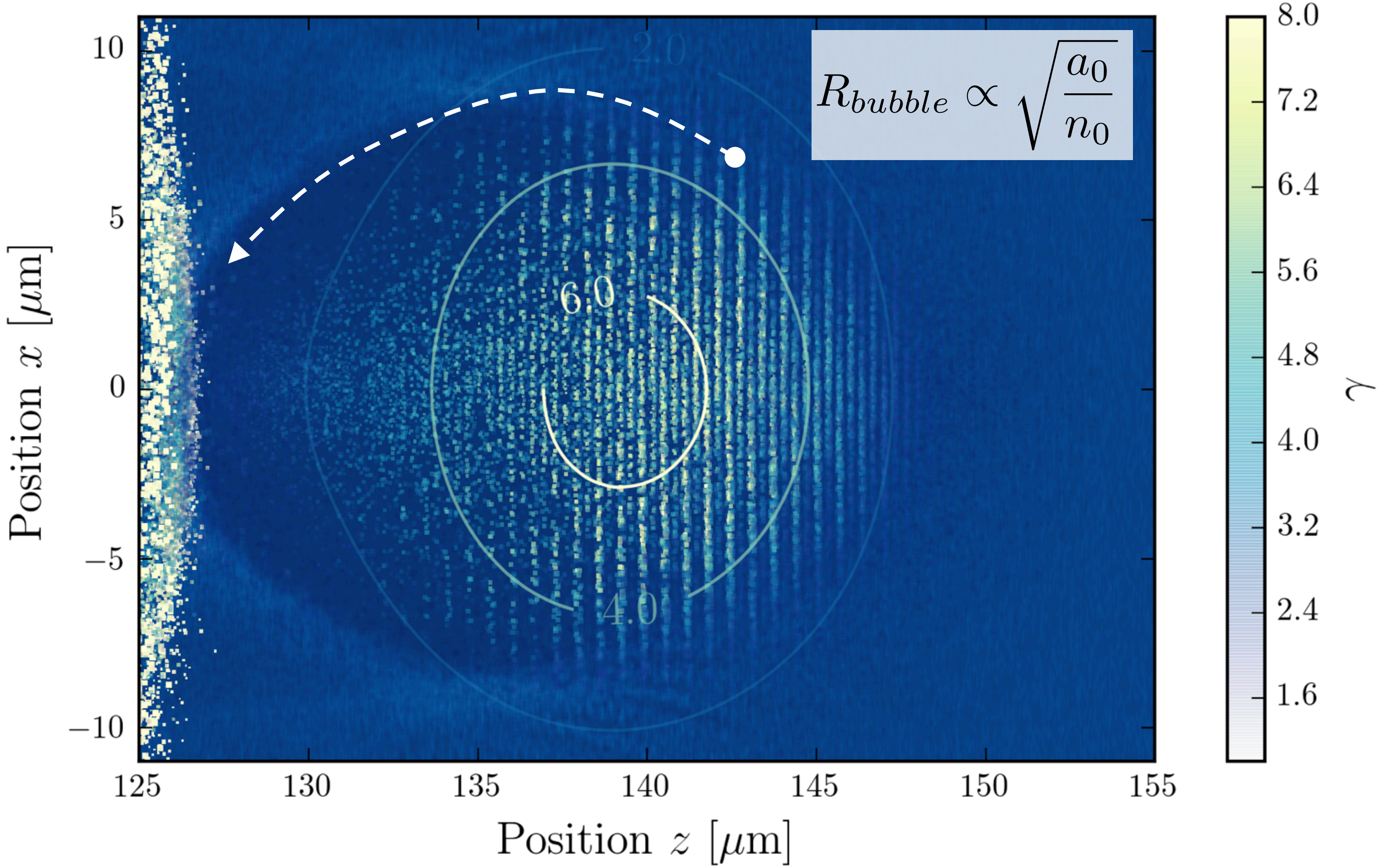
Talk outline

- Laser wakefield acceleration
- Electron dephasing
- Adapting the wake velocity
- Experimental results & discussion

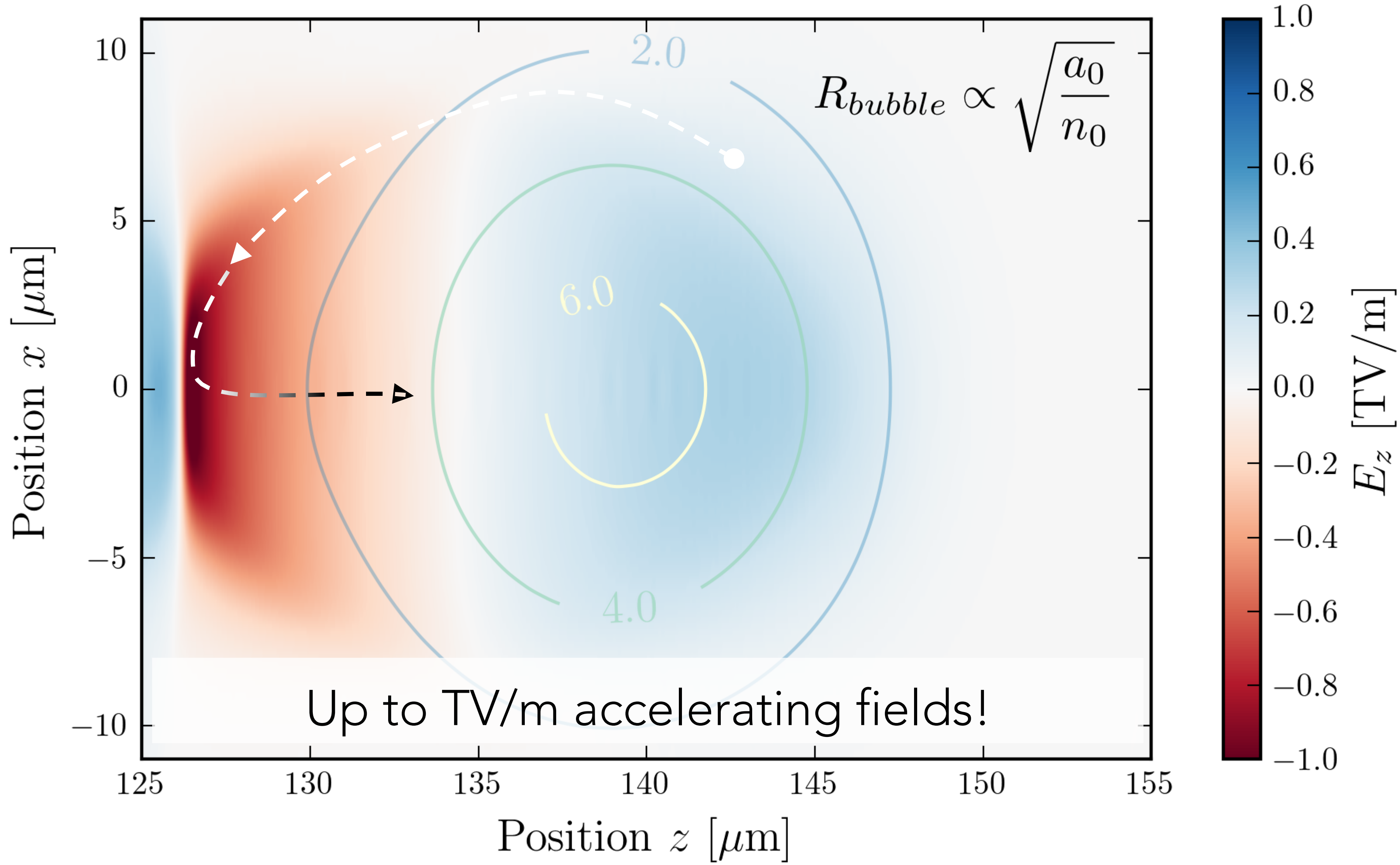
Laser wakefield acceleration

in the blowout regime



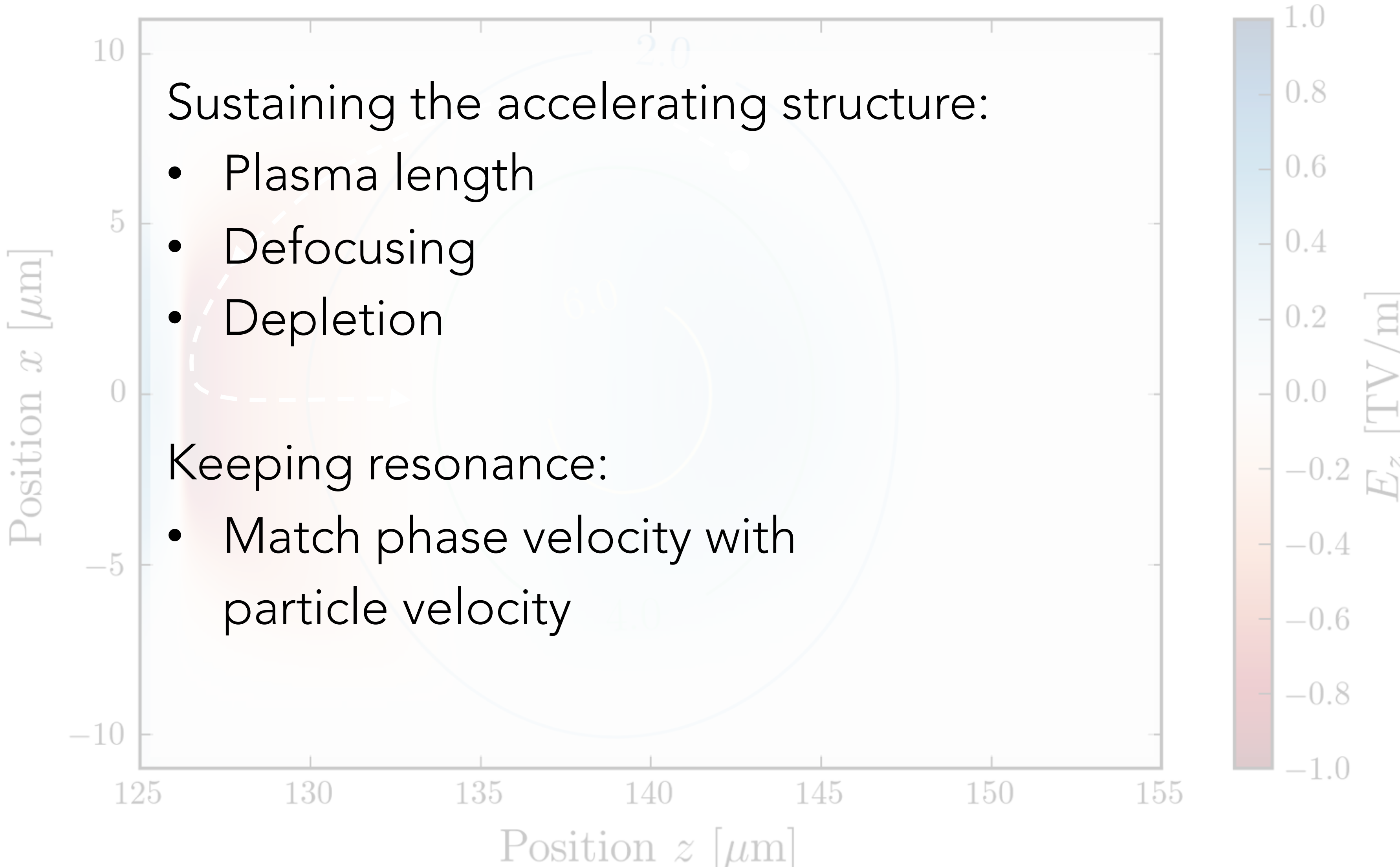
Laser wakefield acceleration

in the blowout regime



Limits on energy gain

in a resonance accelerator



Sustaining the accelerating structure:

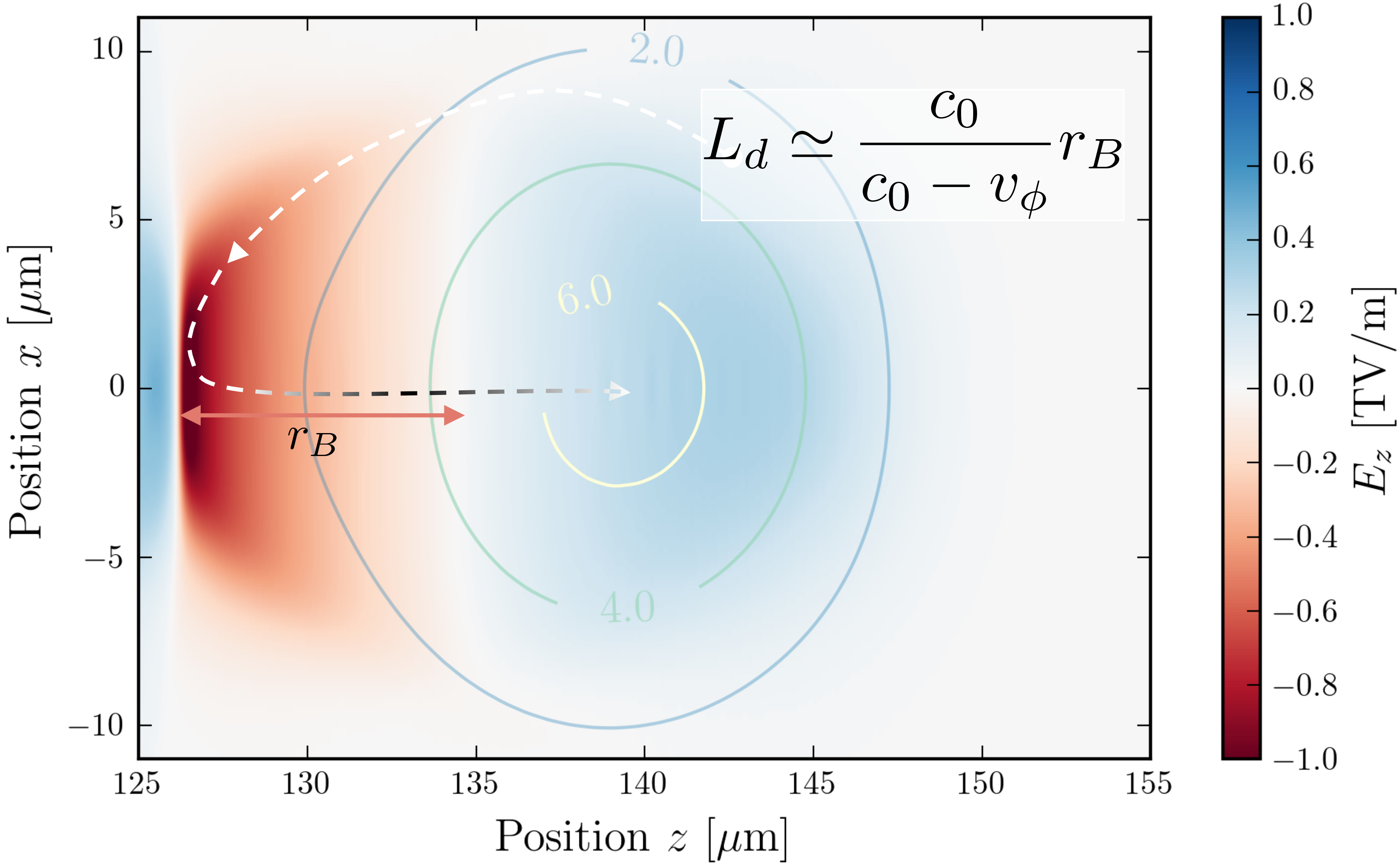
- Plasma length
- Defocusing
- Depletion

Keeping resonance:

- Match phase velocity with particle velocity

Limits on energy gain

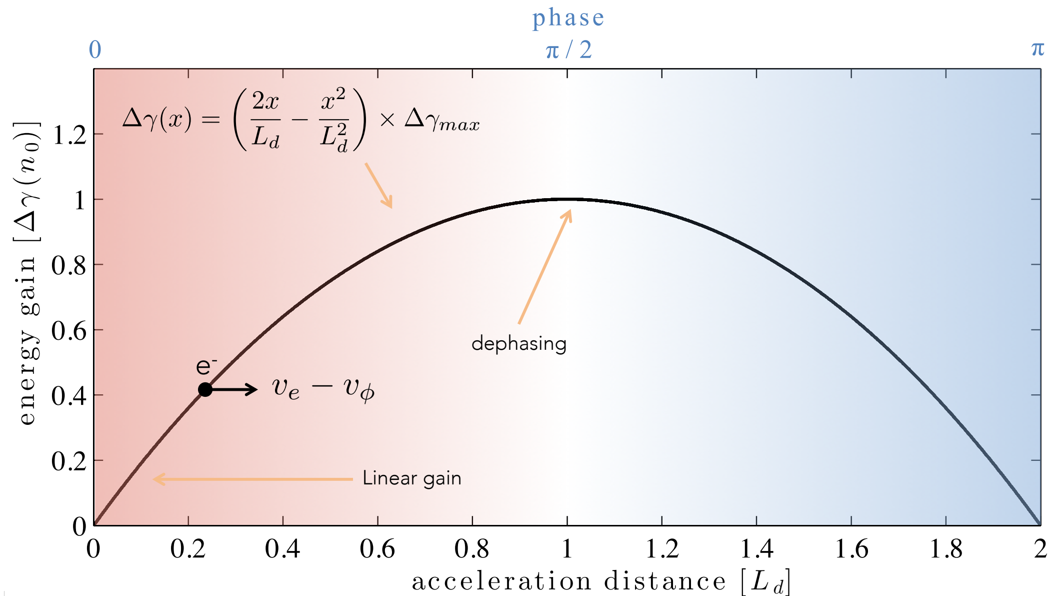
Electron dephasing

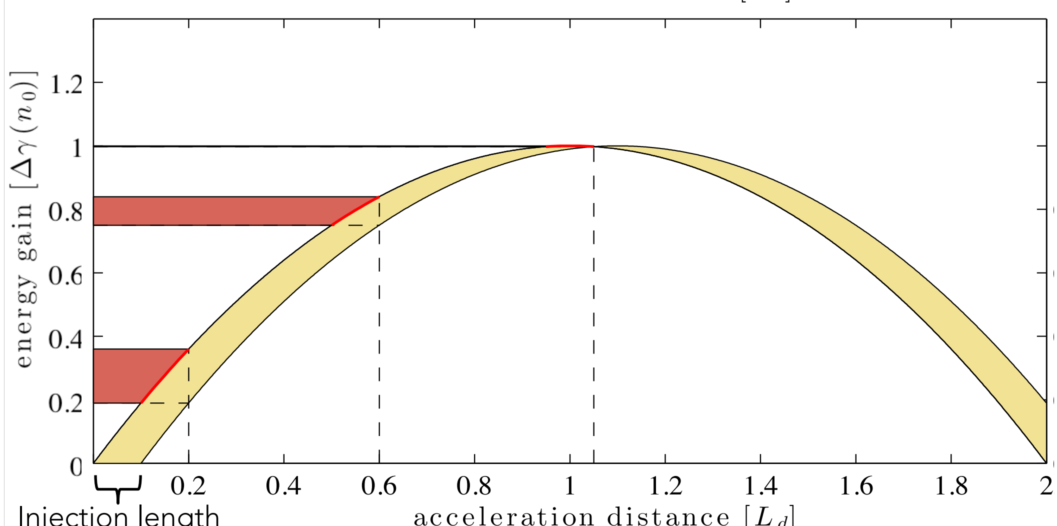


Limits on energy gain

Electron dephasing

- Dephasing reduces efficiency of LWFA
- Dephasing is the final limit on energy gain
- But: Dephasing reduces energy spread
- Can we increase the gain of a dephasing limited accelerator?





Limits on energy gain

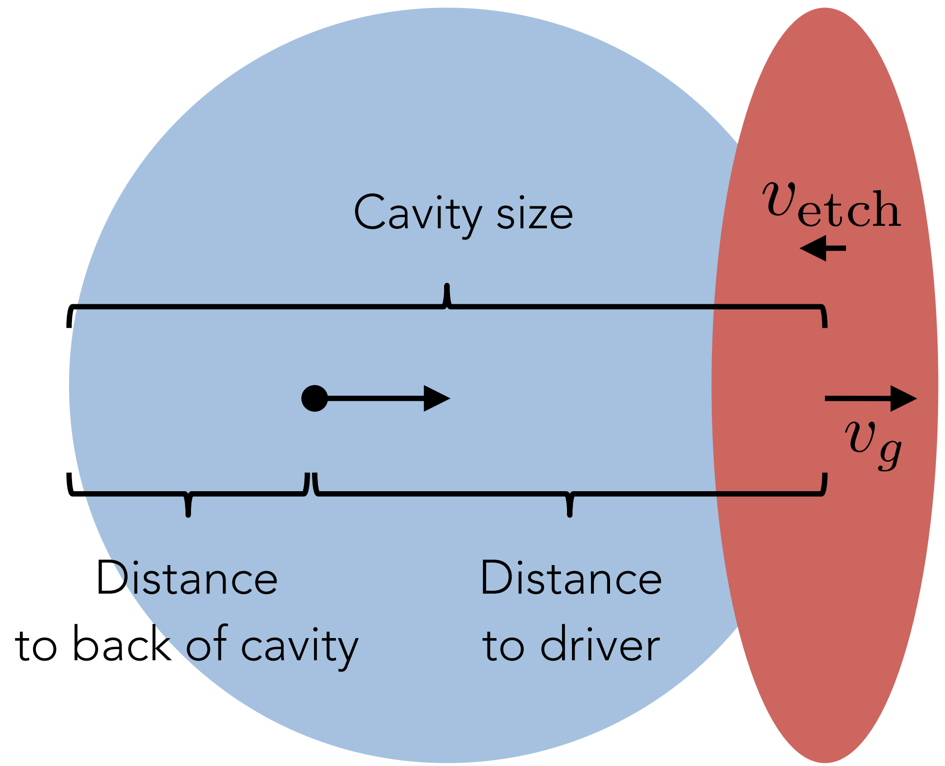
Electron dephasing

$$L_d \simeq \frac{c_0}{c_0 - v_\phi} r_B$$

What is the phase velocity of the wake?

Non evolving bubble:

- Group velocity $1 - \frac{n_e}{2n_c}$
- Etching $-\frac{n_e}{n_c}$



$$E_z \simeq -\frac{m_e \omega_p^2}{2e}(1-\phi) r_B$$

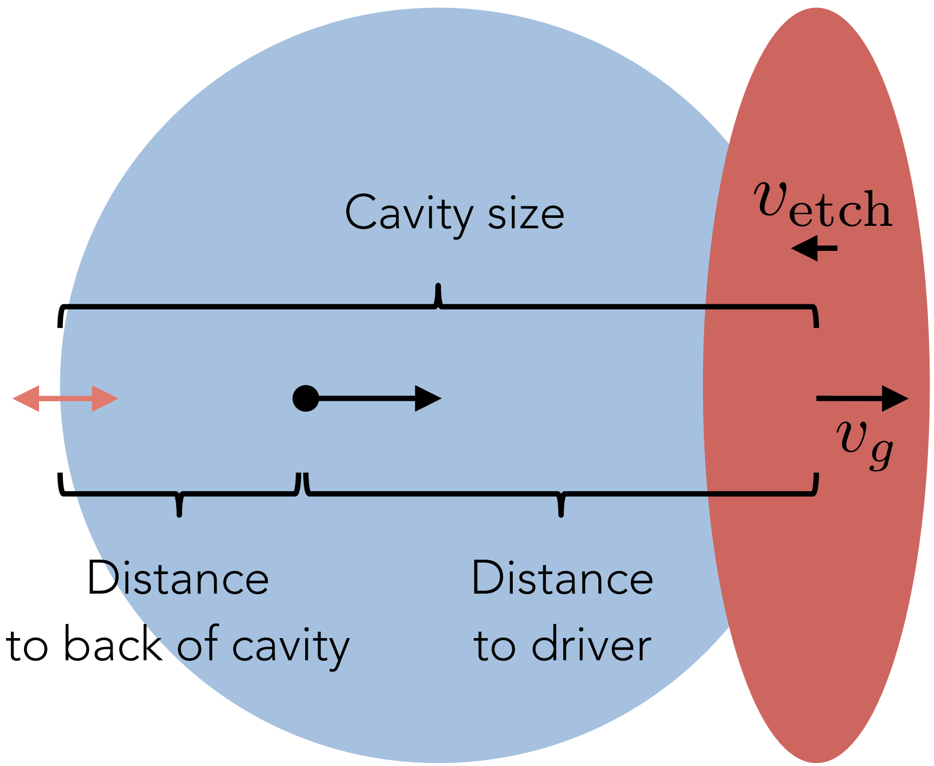
$$\phi = \frac{\text{Distance to back}}{\text{Cavity size}}$$

Limits on energy gain

Electron dephasing

$$L_d \simeq \frac{c_0}{c_0 - v_\phi} r_B$$

What is the phase velocity of the wake?



Non evolving bubble:

- Group velocity $1 - \frac{n_e}{2n_c}$
- Etching $-\frac{n_e}{n_c}$

Evolving bubble:

- Additional contraction / expansion term

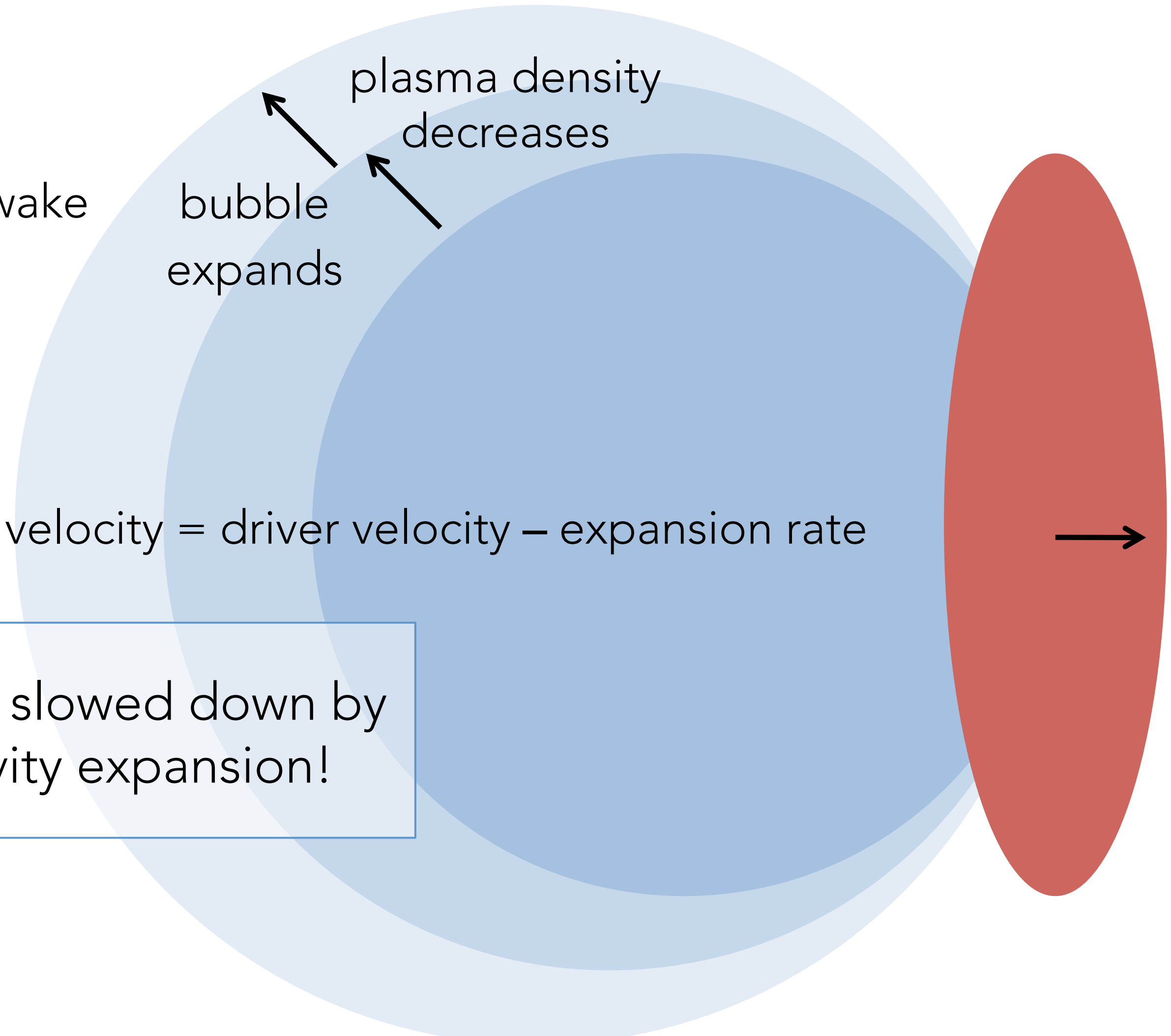
$$E_z \simeq -\frac{m_e \omega_p^2}{2e}(1-\phi) r_B$$

$$\phi = \frac{\text{Distance to back}}{\text{Cavity size}}$$

Adjusting the wake velocity

Density downramp injection

- Locally slow down plasma wake
- Injection threshold lowered



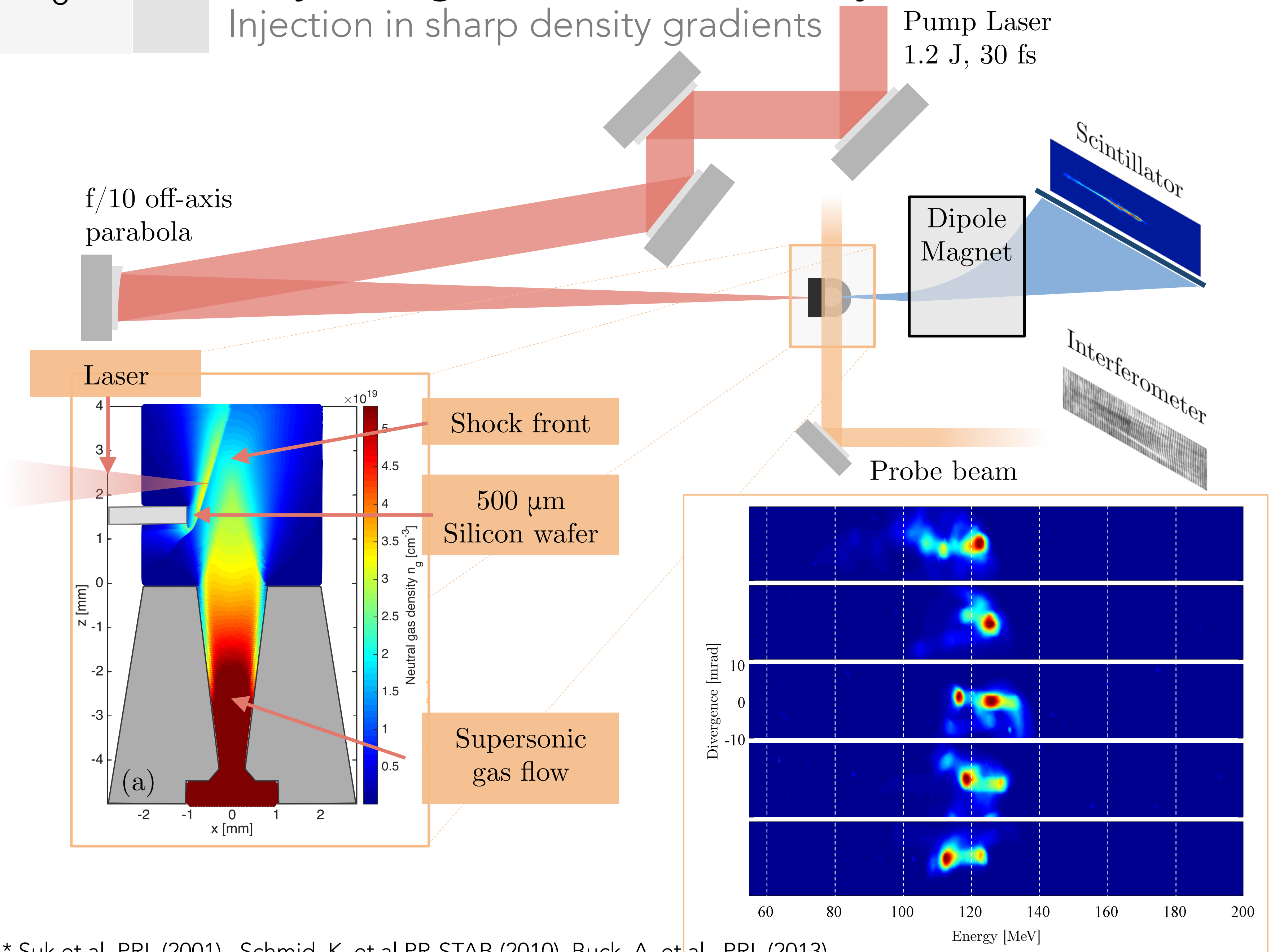
wake velocity = driver velocity – expansion rate

wake slowed down by cavity expansion!

* Bulanov et al. PRE (1998)., Geddes et al., PRL (2008)

Adjusting the wake velocity

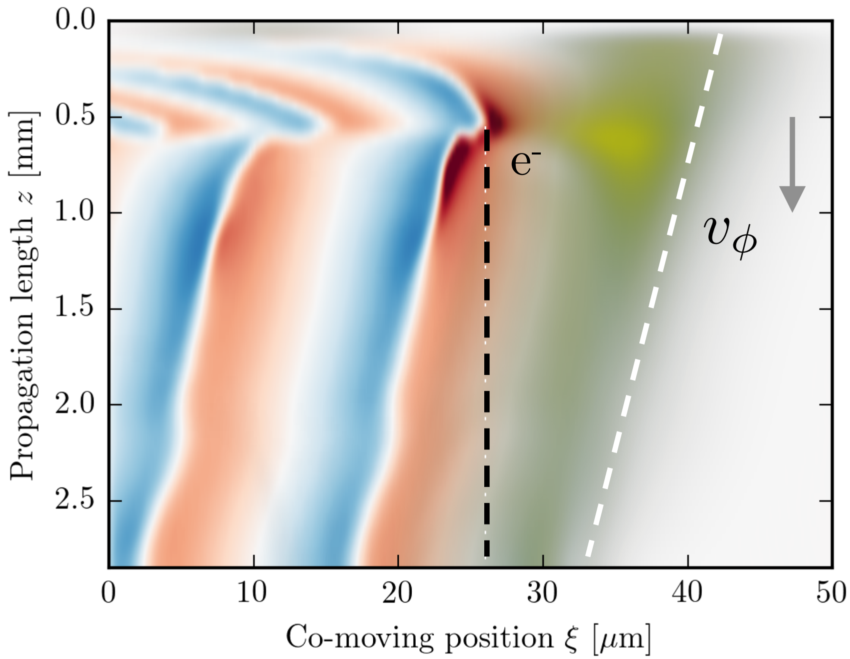
Injection in sharp density gradients

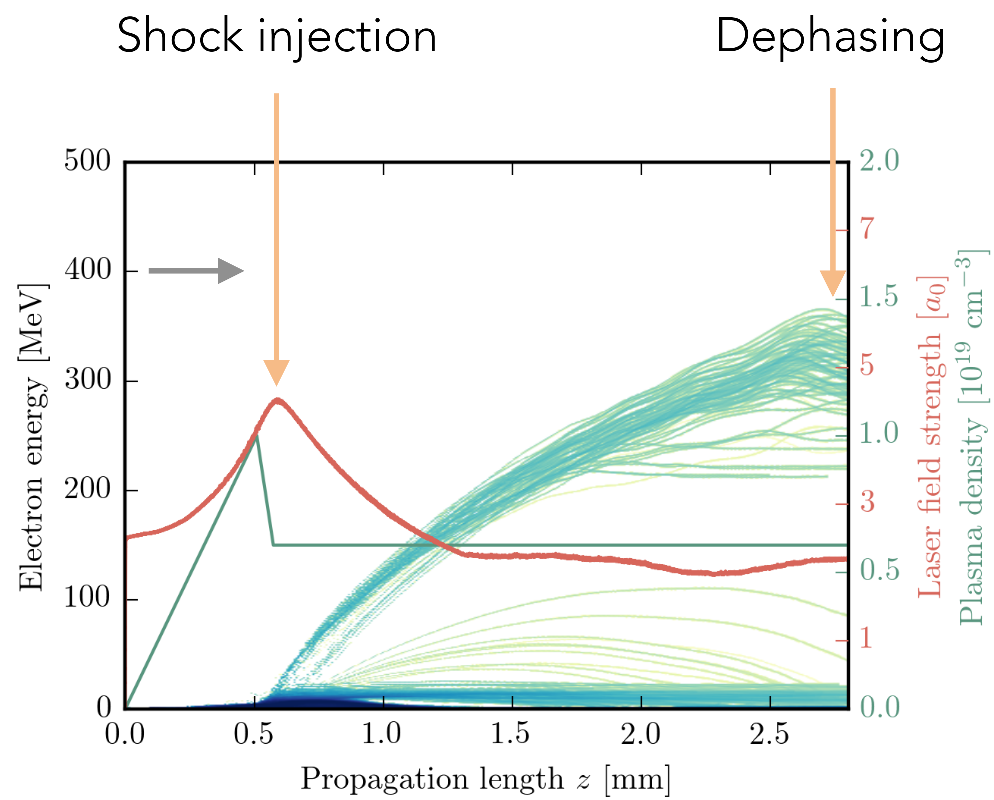


* Suk et al. PRL (2001)., Schmid, K. et al PR-STAB (2010), Buck, A. et al., PRL (2013)

Adjusting the wake velocity

PIC simulation of shock injection



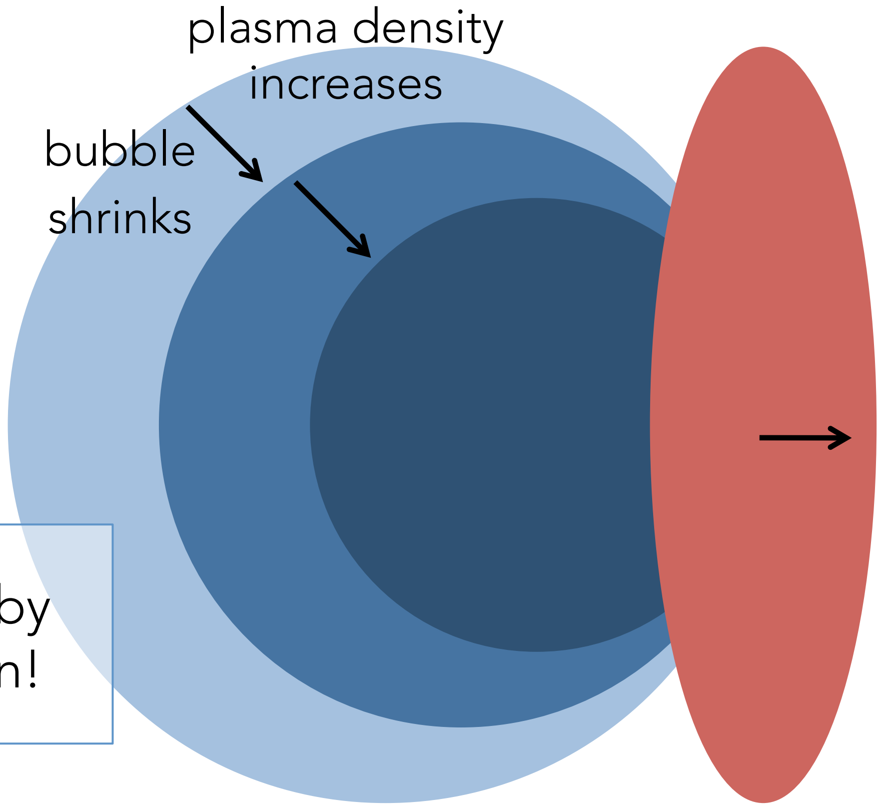


* 1500 x 250 cells, $\Delta x = 0.3\ k_0^{-1}$, $\Delta r=1.5k_0^{-1}$. λ_0=0.8μm.

Adjusting the wake velocity

Electron rephasing

- Invert principle of downramp injection : an increase of plasma density can lead to bubble contraction
- Electron is rephased



wake speeds up by cavity contraction!

Adjusting the wake velocity

Electron rephasing

- Invert principle of downramp injection : an increase of plasma density can lead to bubble contraction
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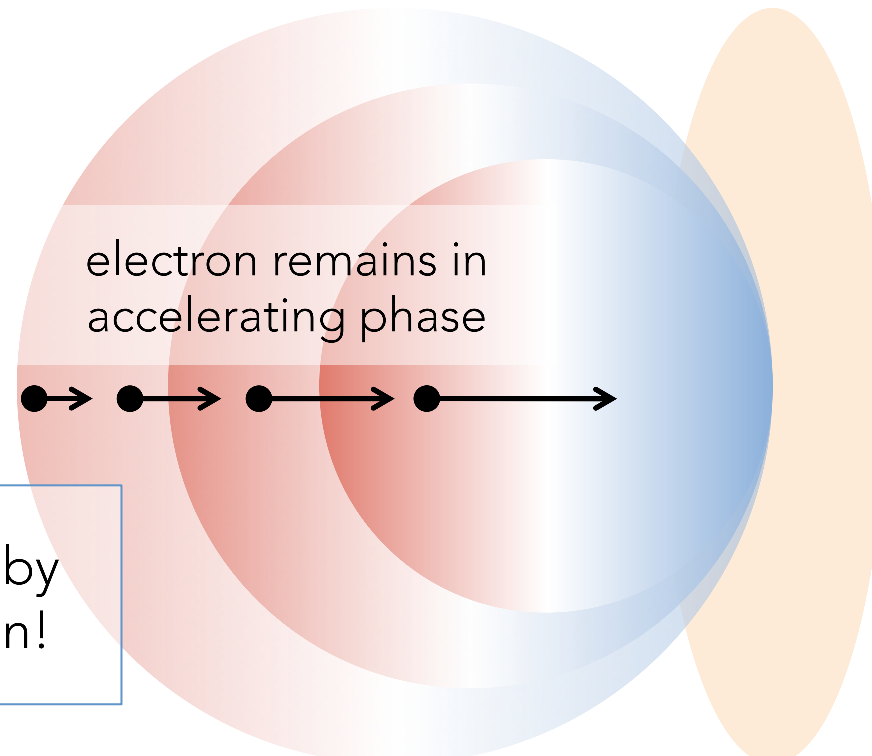


wake speeds up by cavity contraction!

- Theoretical framework only developed for phase locking in linear regime
- Non-linear regime is more complex due to self-focusing

* e.g. Sprangle et al., PRE 2001, Pukhov et al., PRE 2008, Rittershofer et al. PoP 2010

Adjusting the wake velocity

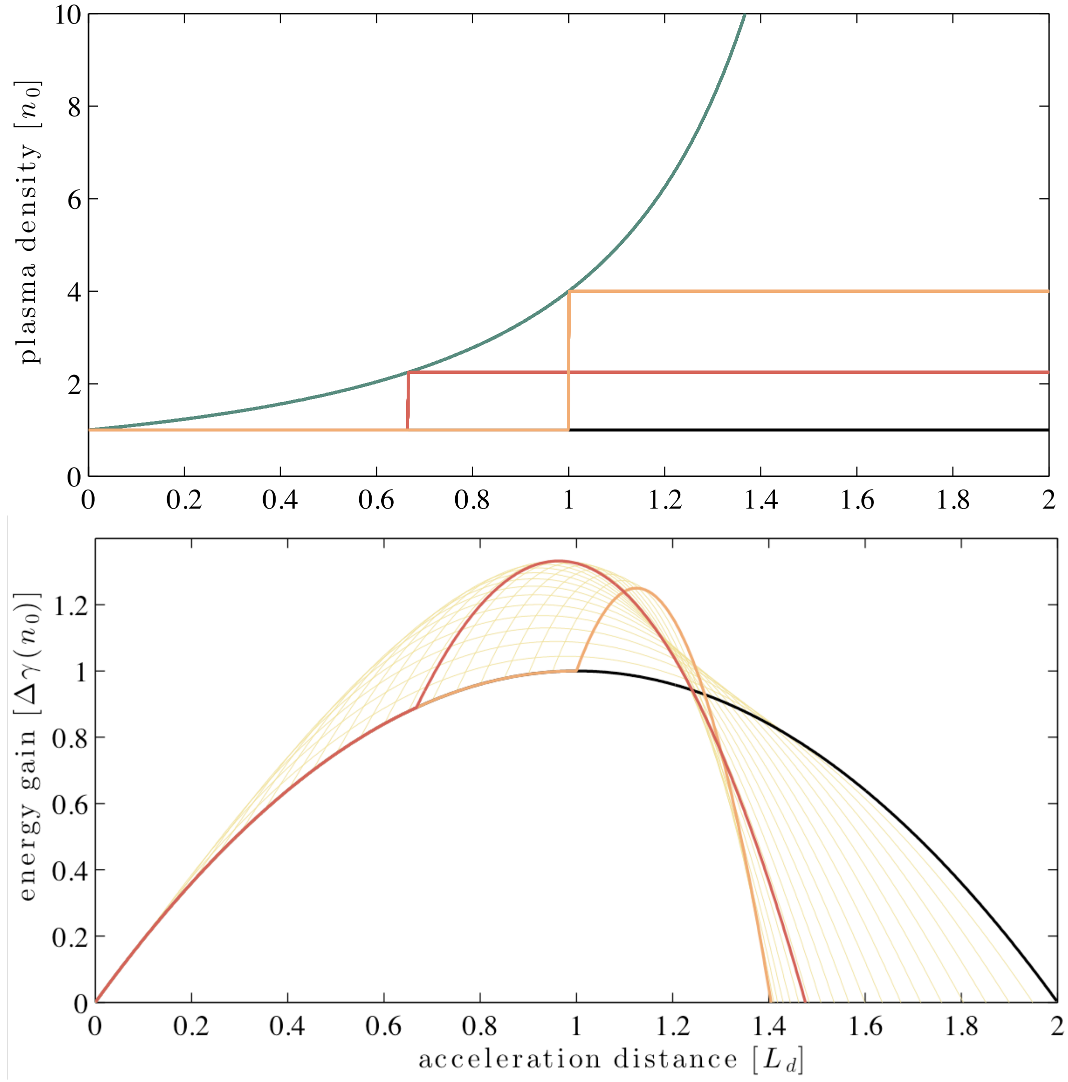
Electron rephasing

Propose phase reset instead of phase locking!*

Gain estimation* for complete instantaneous phase reset at different position x :

$$\Delta\gamma_{max}(x_{boost}) = \left(1 + \frac{x}{L_d} - \frac{3}{4}\frac{x^2}{L_d^2}\right) \times \Delta\gamma_{max}(n_0)$$

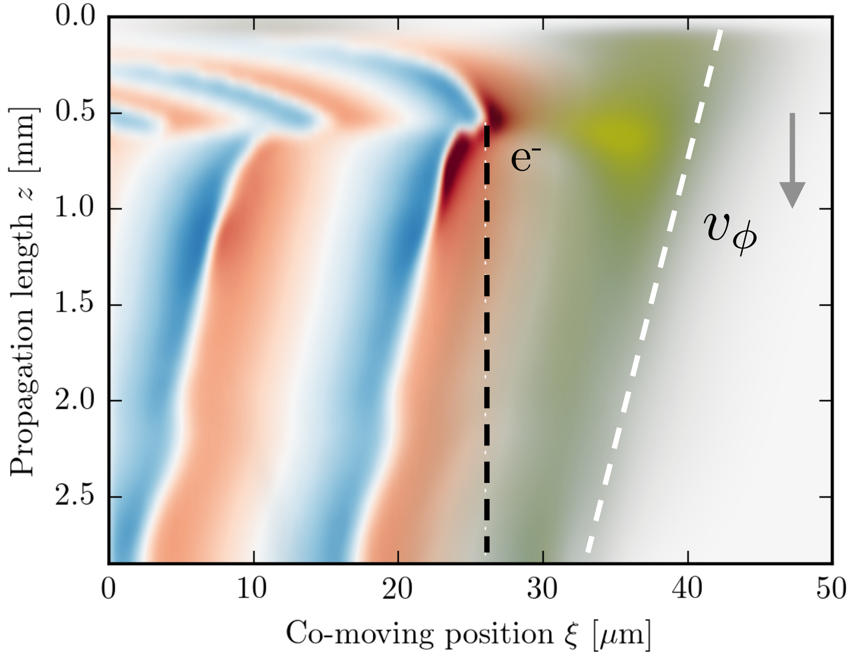
maximum gain of ~ 30 percent close to dephasing length

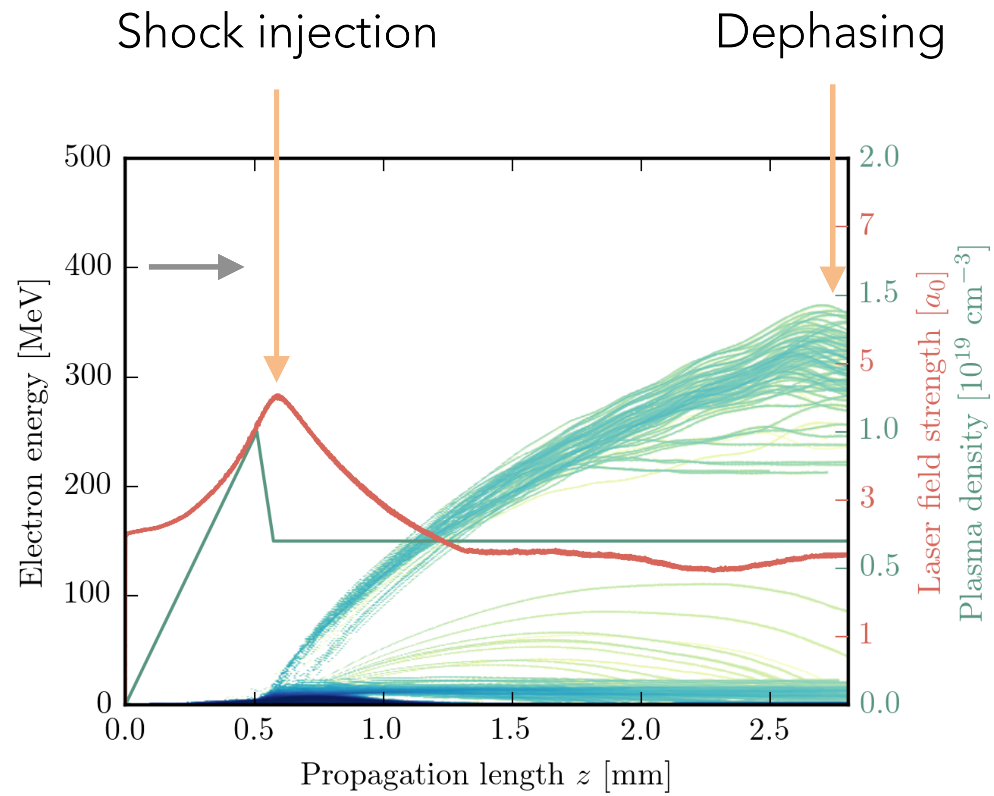


* Ta Phuoc et al., PoP (2008)

Adjusting the wake velocity

PIC simulations of acceleration with density step





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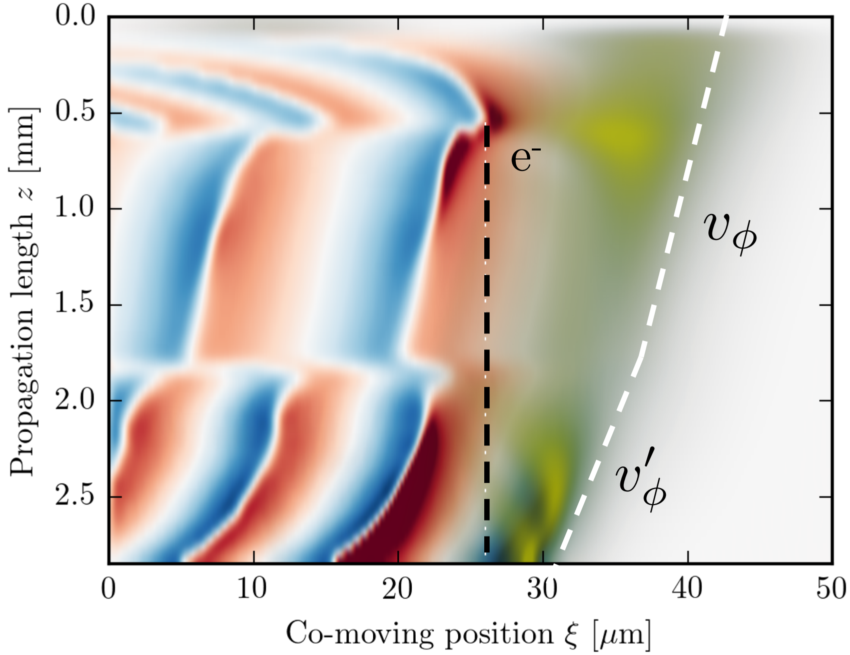
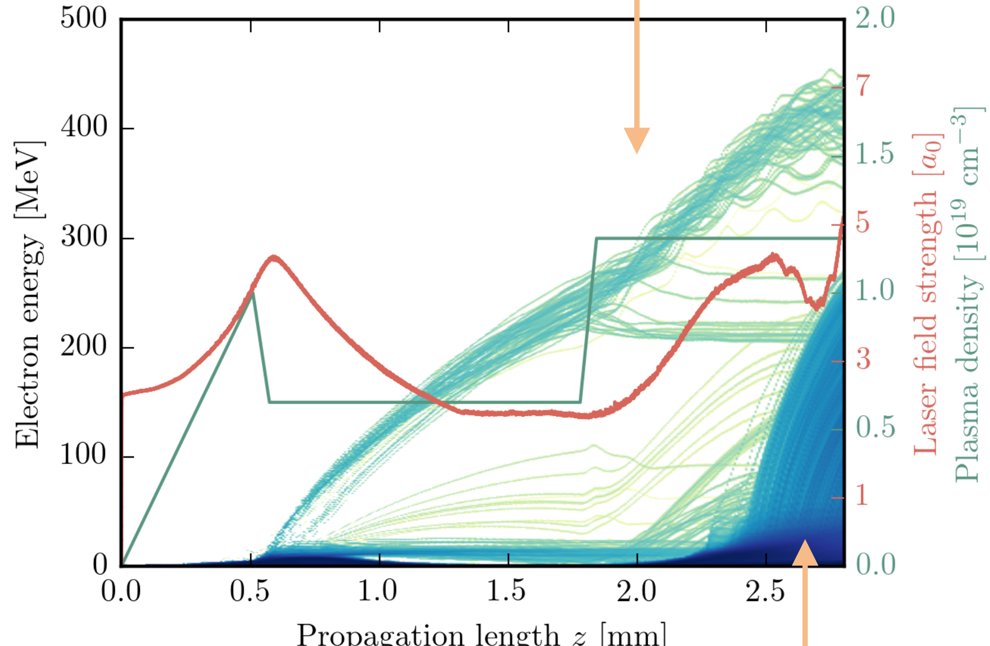
Adjusting the wake velocity

PIC simulations of acceleration with density step



Rephasing

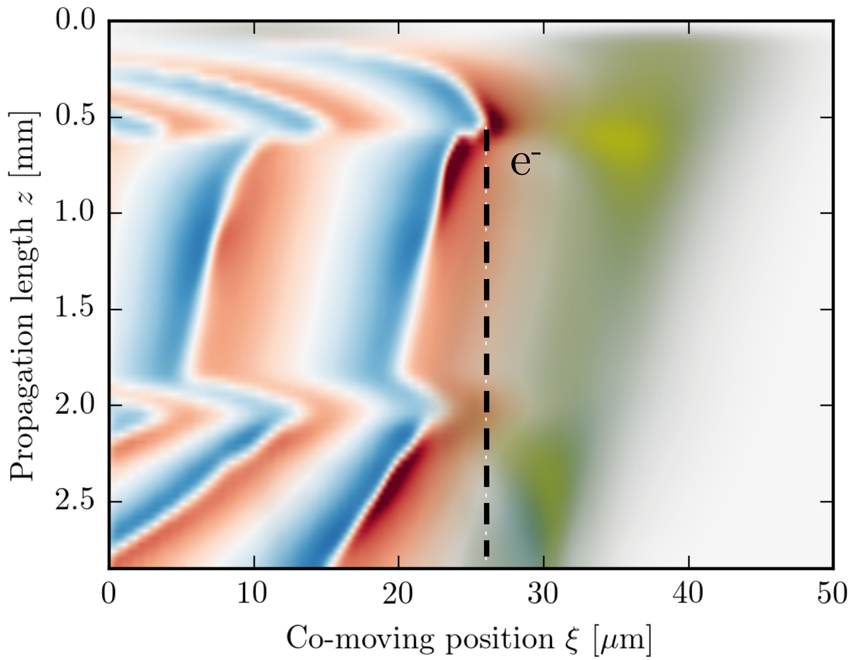


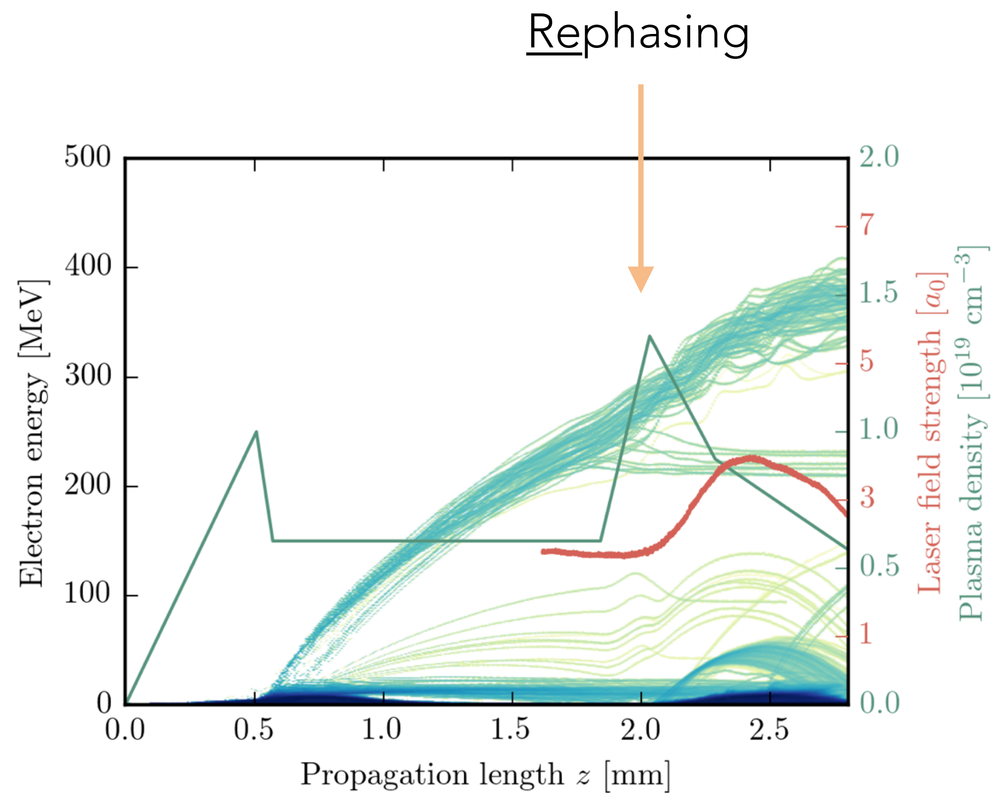
Self-injection

* 1500 x 250 cells, $\Delta x = 0.3\ k_0^{-1}$, $\Delta r = 1.5 k_0^{-1}$. $\lambda_0 = 0.8\mu m$.

Adjusting the wake velocity

PIC simulations of acceleration with density step

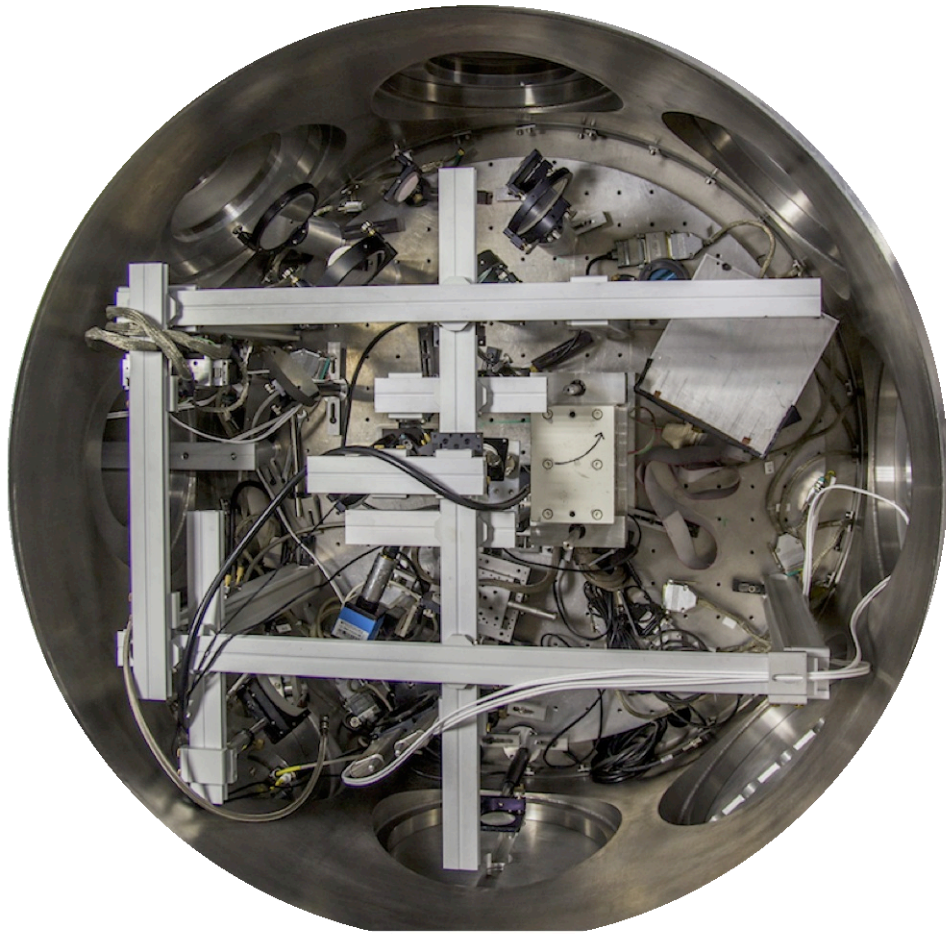




… so shocks might work better!

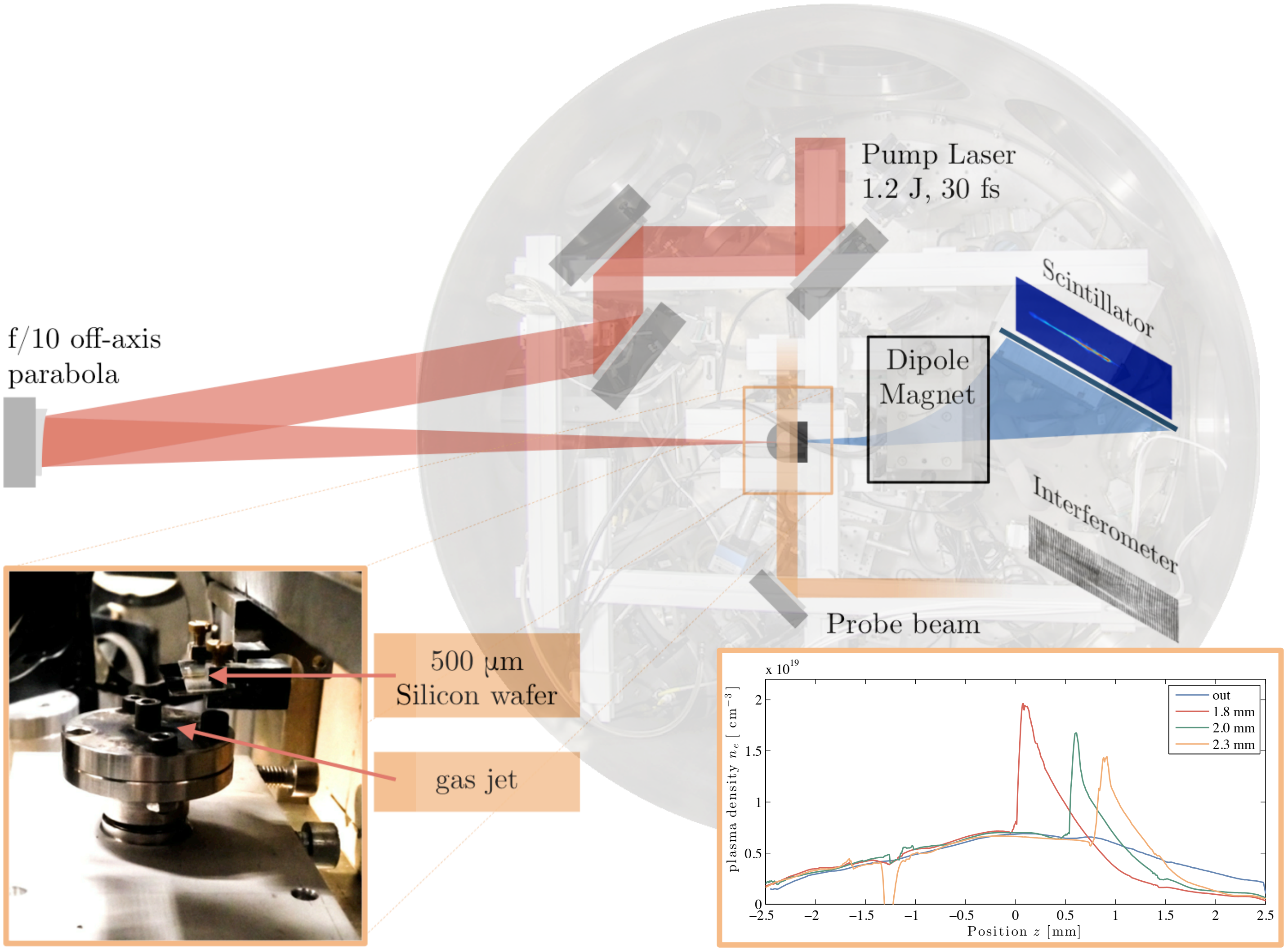
* 1500 x 250 cells, $\Delta x = 0.3\ k_0^{-1}$, $\Delta r=1.5k_0^{-1}$. λ_0=0.8μm.

Experimental setup



Experimental setup

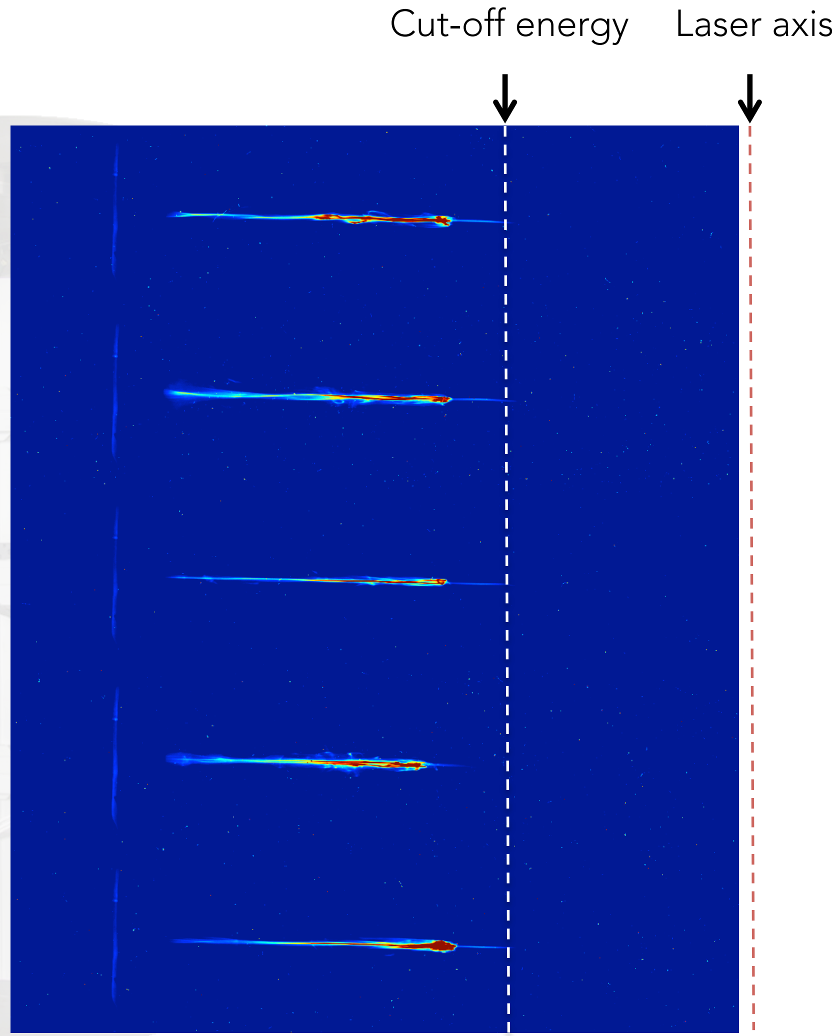
Turn around shock front injector setup



Experimental results

Raw data

raw LANEX data of 5 consecutive shots
without density transition



Experimental results

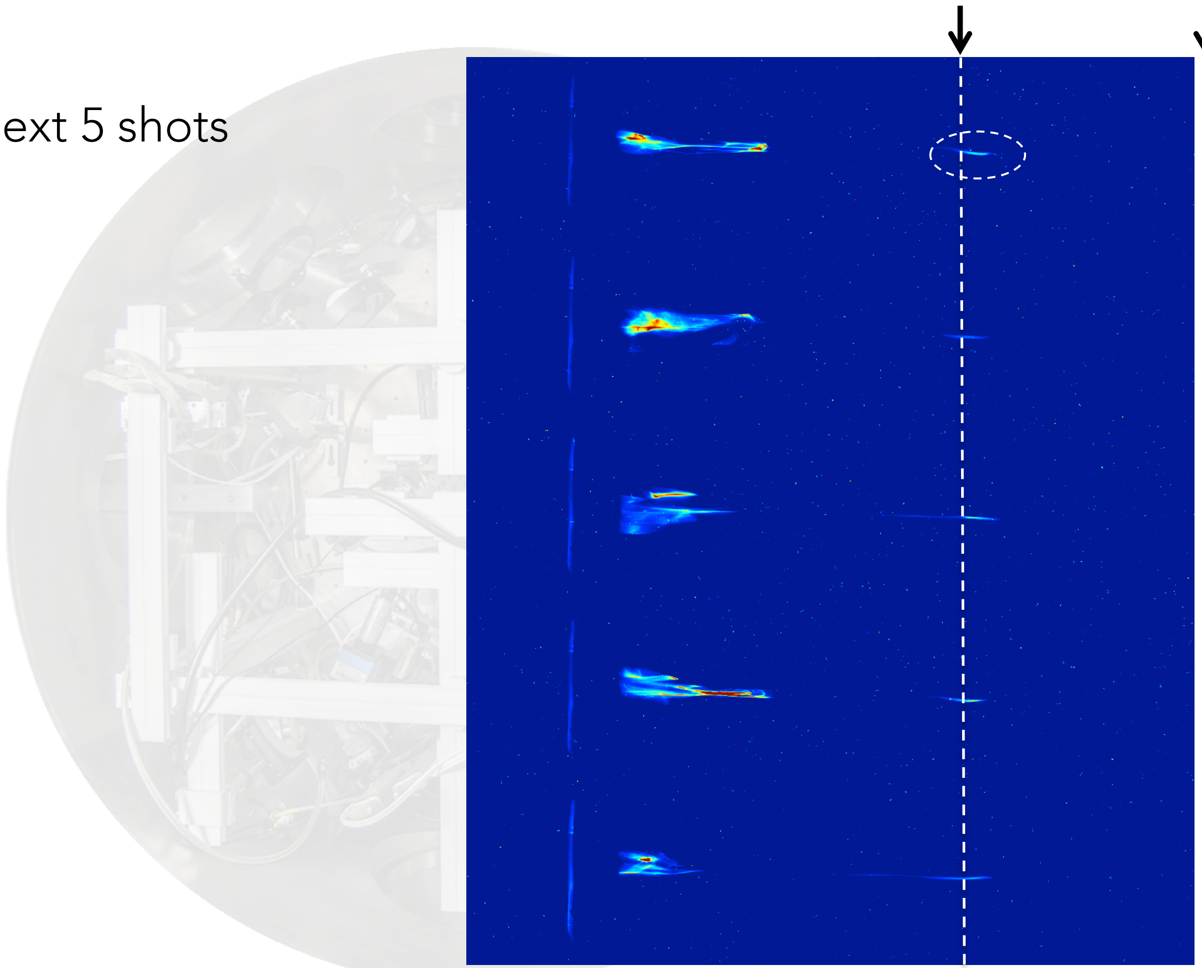
Raw data

raw LANEX data of the next 5 shots

<u>with</u> density transition

Cut-off energy

Laser axis



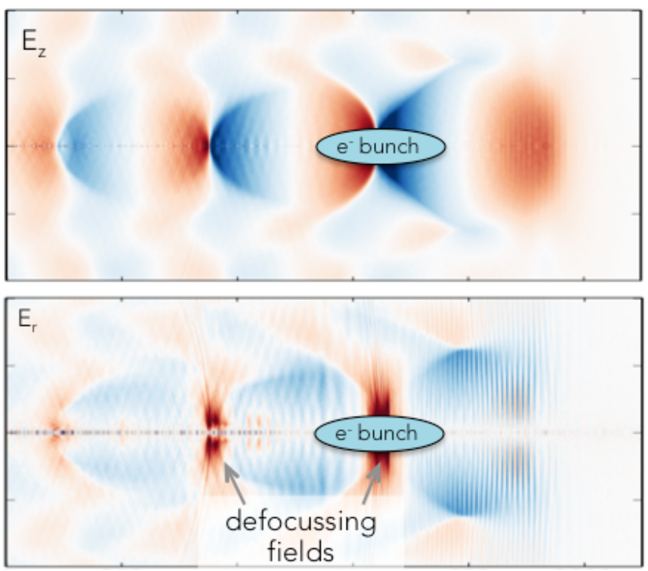
Electrons accelerated

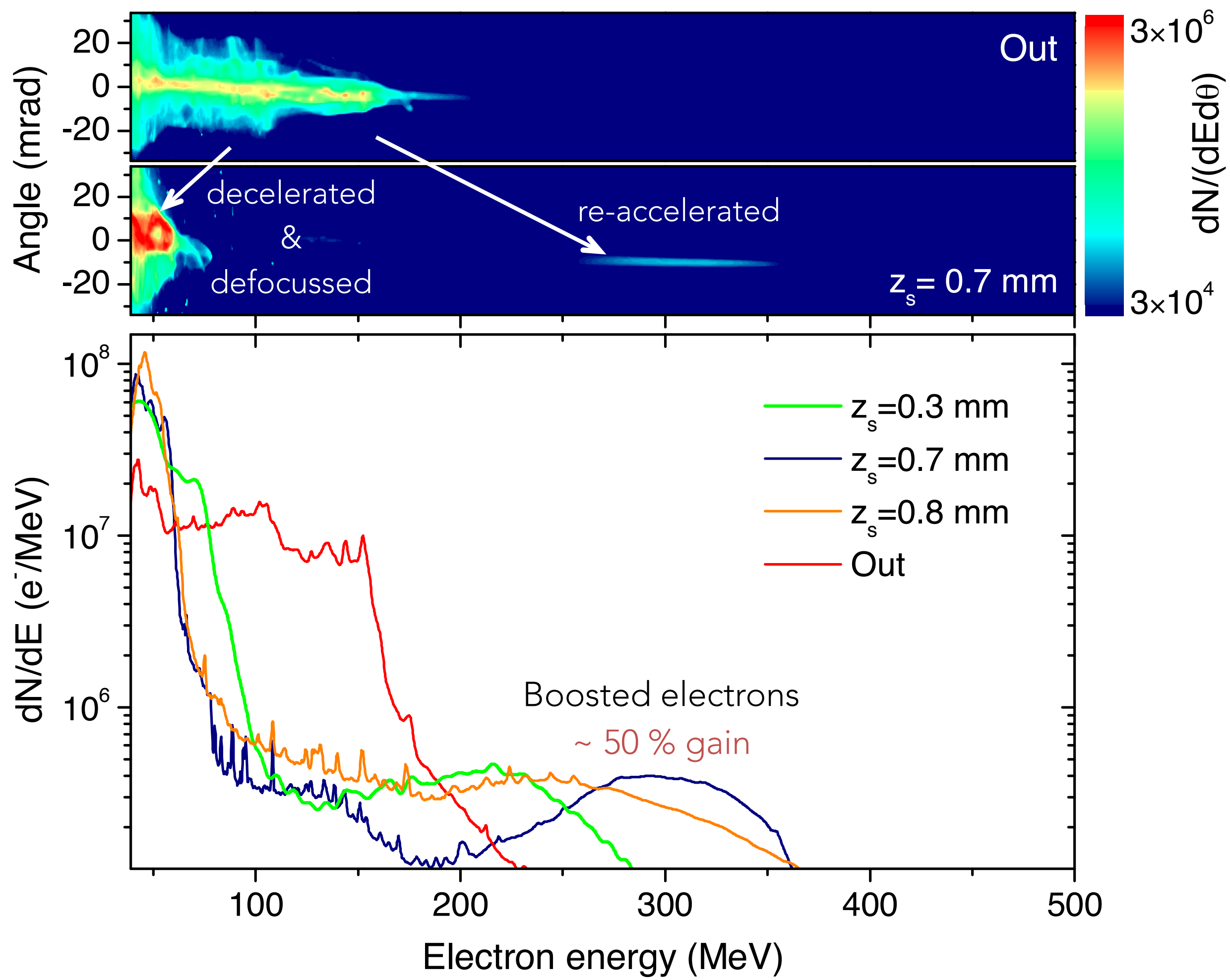
beyond cut-off

Experimental results

Deconvolved data

- Electrons accelerated beyond cut-off
- Rear part of the bunch is decelerated and defocussed



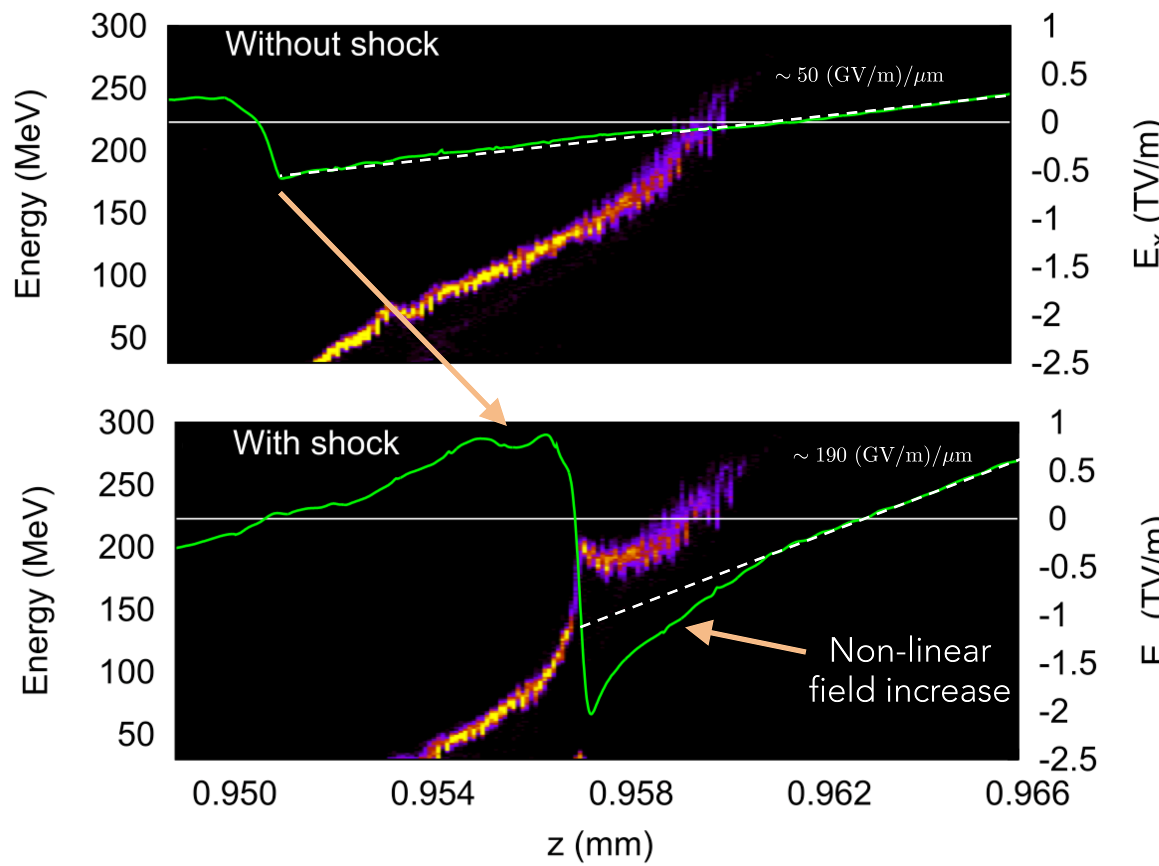


* Submitted

Experimental results

Comparison to PIC for experimental parameters

- Observe non-linear field increase at the rear of the bubble
- Rotation in z/p_z space reduces energy spread : (leads to quasi-monoenergetic beam)

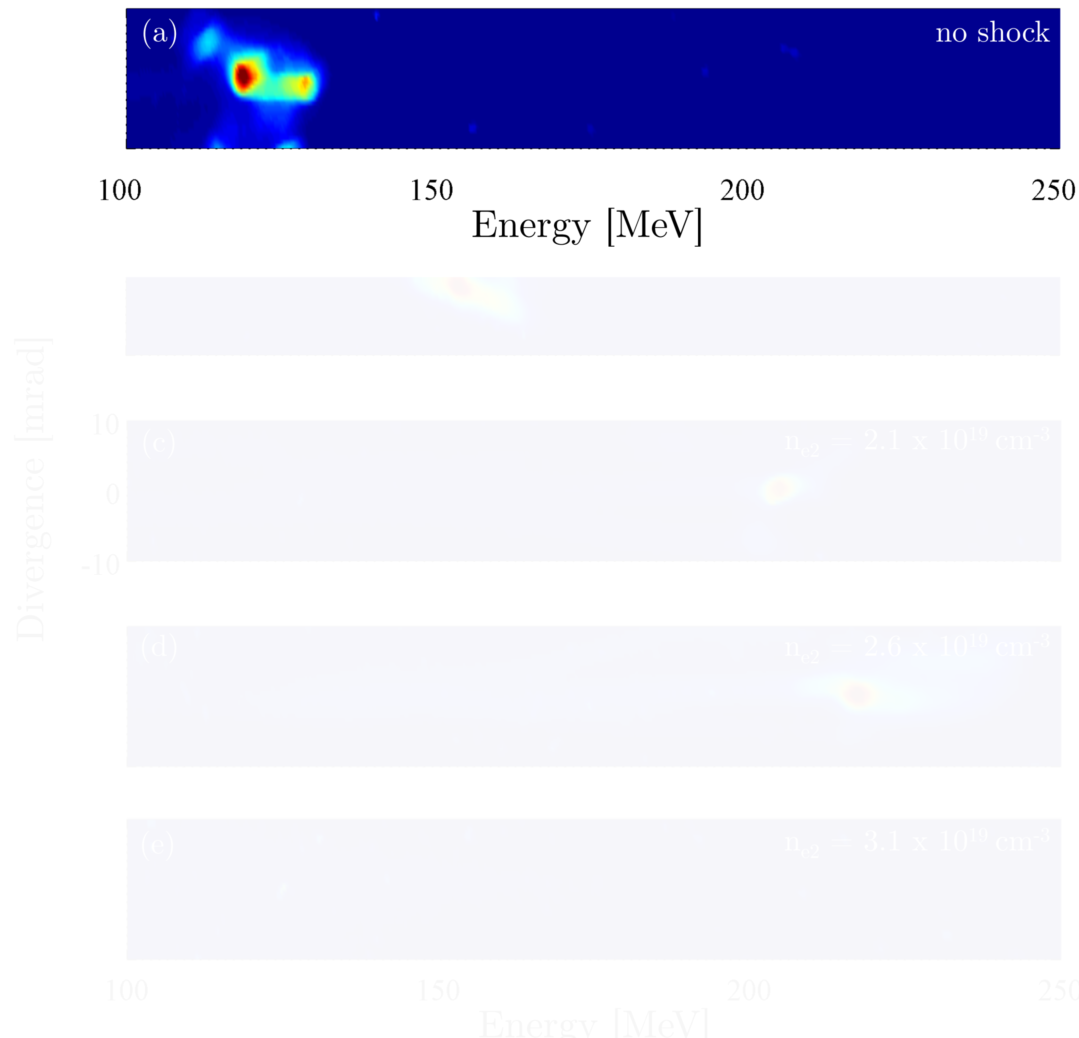


* 3672 x 400 cells, $\Delta x = 0.3\ k_0^{-1}$, $\Delta r = 1.5 k_0^{-1}$. $\lambda_0 = 1 \mu m$.

Experimental results

Energy gain of monoenergetic beams

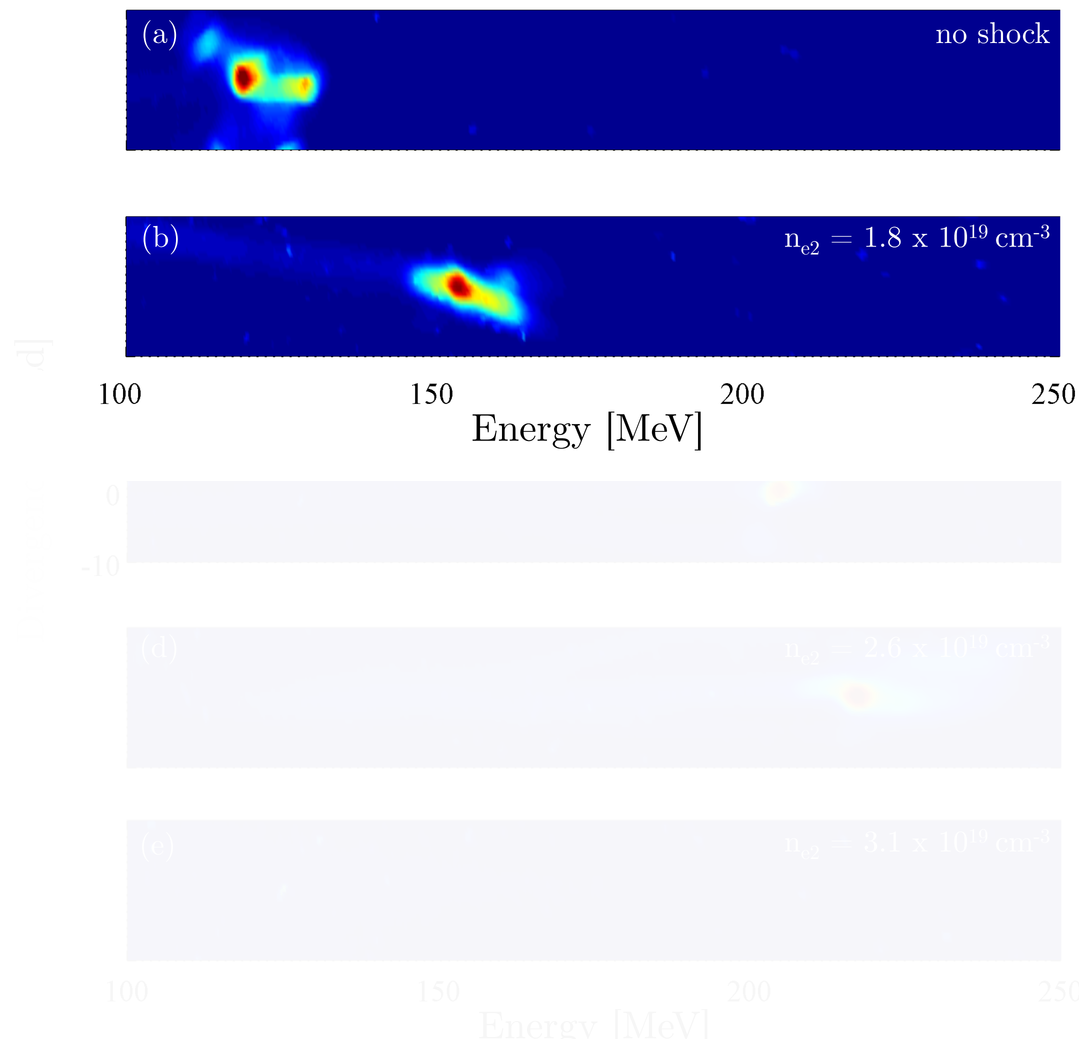
- Electrons injected via shock front injection



Experimental results

Energy gain of monoenergetic beams

- Electrons injected via shock front injection
- Energy increases with backing pressure of second jet



Experimental results

Energy gain of monoenergetic beams

- Electrons injected via shock front injection
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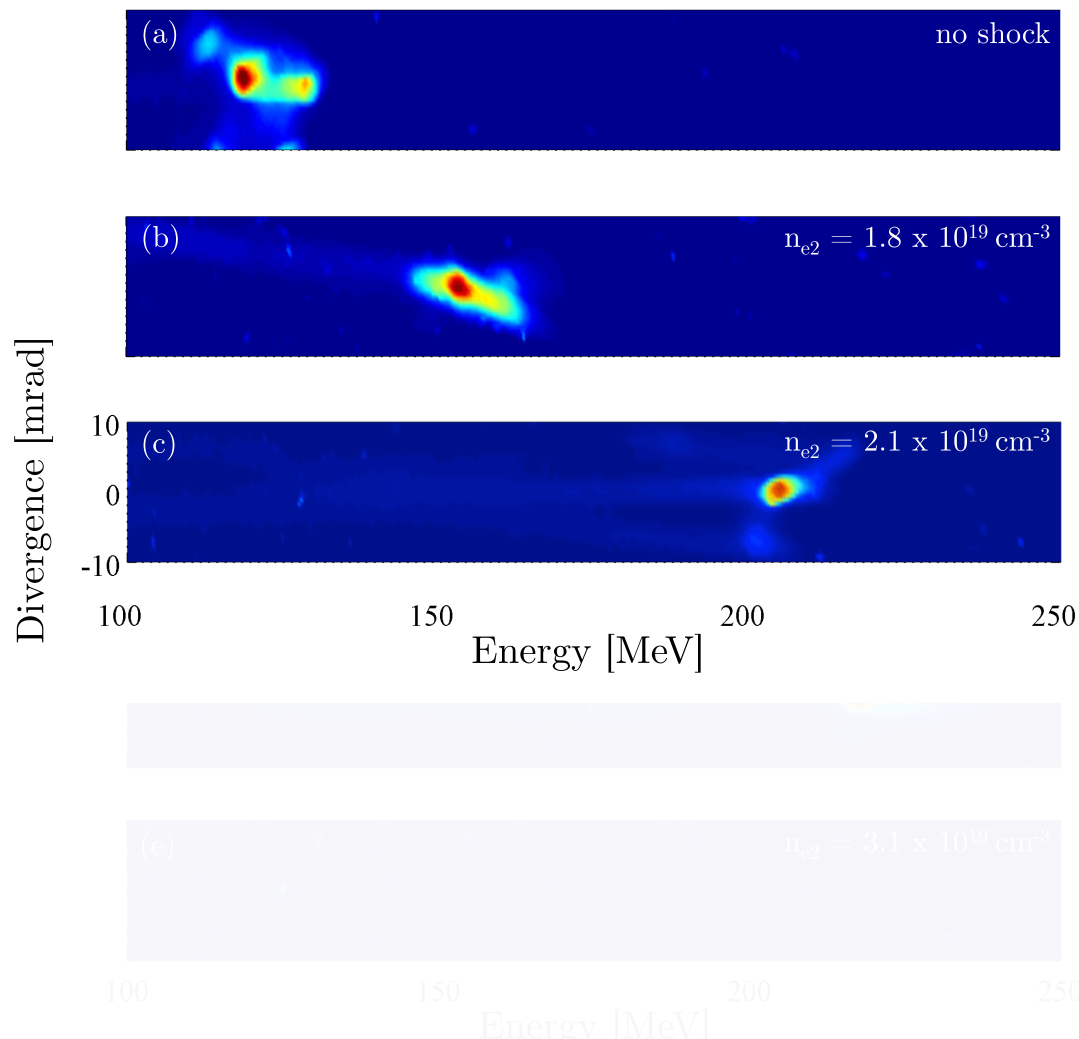

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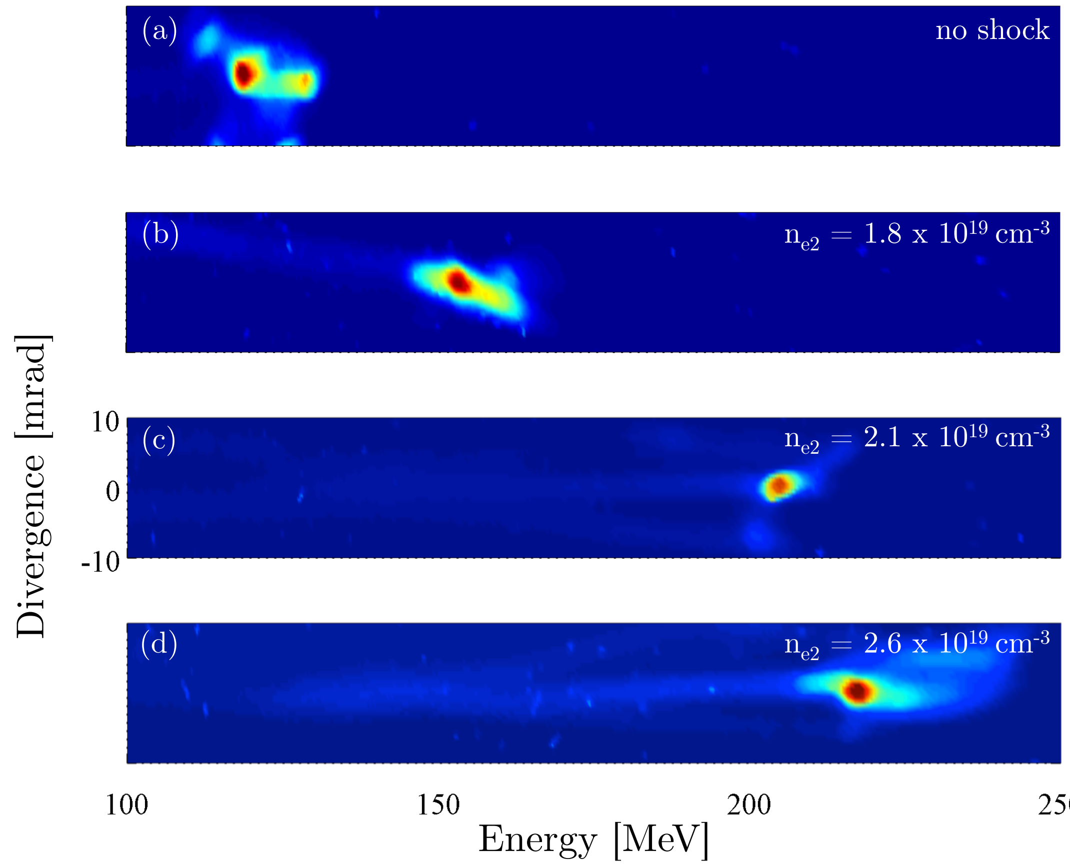
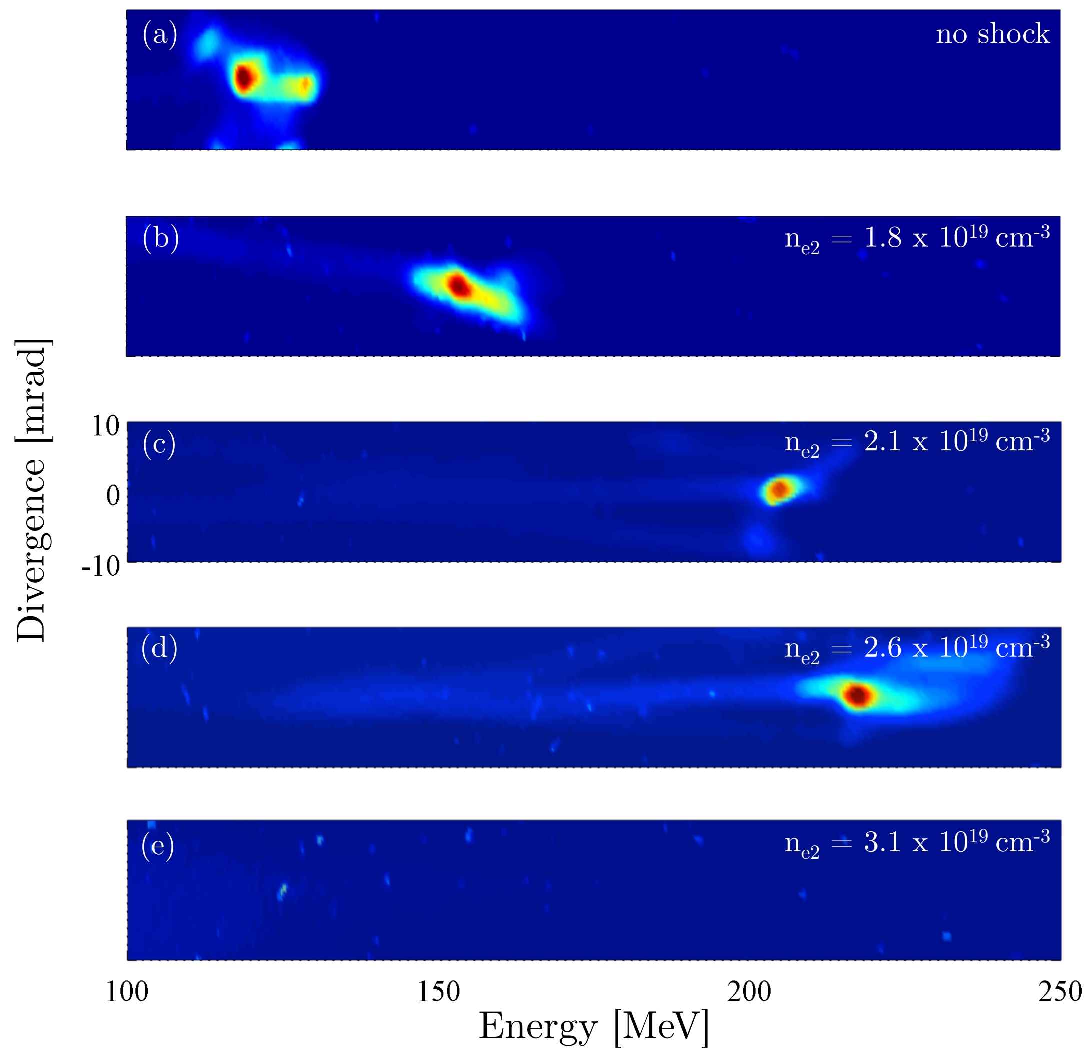


Experimental results

Energy gain of monoenergetic beams

- Electrons injected via shock front injection
- Energy increases with backing pressure of second jet
- At high pressure electrons are entirely defocused



Conclusions

- Dephasing effects can be mitigated by density tailoring
- Simple experimental setup (shock front)
- Observed gain of ~50 %,
  exceeding linear E-field model (~30%)
- Best suited for monoenergetic beams

By the way: electrons never leave the bubble, same laser, same jet – in contrast to staging …

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Thank you for your attention!

btw.

Setup for rephasing of shock injected beams