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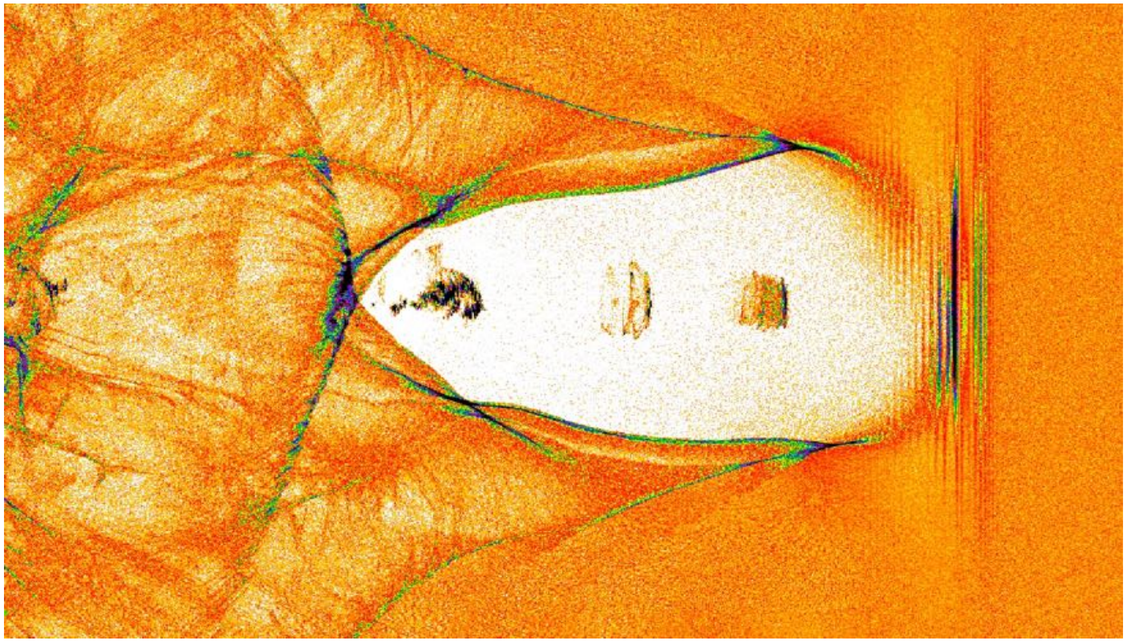
Laser-plasma electron acceleration in a strongly-mismatched regime

Aakash Sahai

Dept of Physics
& John Adams Institute
Imperial College London
South Kensington, London



Outline

- motivation – high-energy e^- acceleration – self-guiding laser
- matched regime – optimum ?
- mismatched regime – high-energy / high-quality / high-efficiency beam production ?
- adjusted a_0 model – answers some questions ?
- optical shock excitation - over narrow density range
- laser-plasma interactions & beam property - evolution
- Summary

Matched regime of nonlinear plasma wave

laser ponderomotive force balanced by nonlinear plasma response

matched laser waist size & bubble radius

$$w_0 \simeq 2\sqrt{a_0}\ \frac{c}{\omega_{pe}} \equiv R_{\text{bubble}}$$

energy gain in matched regime

$$\Delta\mathcal{E}\ [m_e c^2] \simeq \frac{2}{3}\ a_0\ \left(\frac{n_c}{n_0}\right)$$

Lu, W., Tzoufras, M., Joshi, C., Tsung, F. S., Mori, W. B., Vieira, J., Fonseca, R. A., Silva, L. O., *Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime* Physical Review Special Topics - Accelerators and Beams 10, 061301 (2007), doi:10.1103/PhysRevSTAB.10.061301.

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Gemini expt. data – electron acceleration

Self-guided laser regime

Kneip, S., et. al., *Near-GeV Acceleration of Electrons by a Nonlinear Plasma Wave Driven by a Self-Guided Laser Pulse*, Phys. Rev. Lett. 103, 035002 (2009), doi:10.1103/PhysRevLett.103.035002.

$$\mathrm{f}/20 \text{ optics at } 5.5 \times 10^{18}\mathrm{cm}^{-3},\ \mathcal{E}_L = 10\mathrm{J}, \mathrm{a}_0 = 3.9$$

$$\Delta\mathcal{E} \text{ eq.2} : < 510 \text{ MeV}$$

$$\text{peak expt. } \Delta\mathcal{E} : 800 \text{ MeV}$$

Aug 2015 f/40 data

$$\mathrm{f}/40 \text{ optics at } 2 \times 10^{18}\mathrm{cm}^{-3},\ \mathcal{E}_L = 10\mathrm{J}, \mathrm{a}_0 \simeq 1.9$$

$$\Delta\mathcal{E} \text{ eq.2} : < 1 \text{ GeV}$$

$$\text{peak expt. } \Delta\mathcal{E} : 2.2 \text{ GeV}$$

large degree of mismatch !

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Strongly mismatched regime

Aug 2015 f/40 data expt. parameters

$\mathcal{E}_{\rm L}$, FWHM-τ_p	$\simeq$ 10 J, 49 fs
P_L	$\simeq$ 200 TW
w_{0-y} (y-axis)	37.4 μm
w_{0-z} (z-axis)	44.2 μm
peak a_0 (coupled)	$\simeq$ 1.9
$\Delta\mathcal{E}_{\rm peak}$	2.2 GeV
n_0 (peak energy)	$2-3\times10^{18}$ cm^{-3}
P_c	18.3 – 12.2 TW

$$\mathrm{f}/40 \text{ optics at } 2\times10^{18}\mathrm{cm}^{-3},\ a_0 = 1.9$$

$$w_0(\text{matched}) = 10.3\mu m$$

$$w_0(\text{expt.}) = 37.4\mu m$$

f/20 data expt. Parameter mismatch

$$\mathrm{f}/20 \text{ optics at } 5.5\times10^{18}\mathrm{cm}^{-3},\ a_0 = 3.9$$

$$w_0(\text{matched}) = 8.95\ \mu m$$

$$w_0(\text{expt.}) = 19.0\ \mu m$$

strong mismatch between laser envelope & plasma response

adjusted a_0 model

$$\Delta\mathcal{E}_{\rm adj.}[m_e c^2] = \frac{2\pi}{3}\ \sqrt{a_{0-l}}\ \left(\frac{w_{0-l}}{\lambda_0}\right)\ \sqrt{\frac{n_c}{n_0}}$$

$$\simeq 2.5\ \sqrt{a_{0-l}}\ \sqrt{\frac{n_c}{n_0}}\ \mathrm{F}_l$$

$$\text{circ. :}\quad a_0(\text{adj.}) = a_{0-l}\ \left(\frac{w_{0-l}}{w_{0-m}}\right)$$

$$\text{ellip. :}\quad a_0(\text{adj.}) = a_{0-l}\ \sqrt{\frac{w_{01-l}\ w_{02-l}}{w_{0-m}^2}}$$

based on laser pulse envelope being squeezed to the matched spot-size

2015 f/40 data

$\mathrm{f/40\ optics\ at\ 2\times10^{18}cm^{-3}},\ \mathcal{E}_L = 10\mathrm{J},\ \mathrm{a_0}\simeq 1.9$

$\Delta\mathcal{E}$ eq.2 : $<$ 1 GeV

peak expt. $\Delta\mathcal{E}$: 2.2 GeV

$\Delta\mathcal{E}\ [\mathrm{a_0(adj)} = 7.4]$: 2.2 GeV

2008 f/20 data

$\mathrm{f/20\ optics\ at\ 5.5\times10^{18}cm^{-3}},\ \mathcal{E}_L = 10\mathrm{J},\ \mathrm{a_0} = 3.9$

$\Delta\mathcal{E}$ eq.2 : $<$ 510 MeV

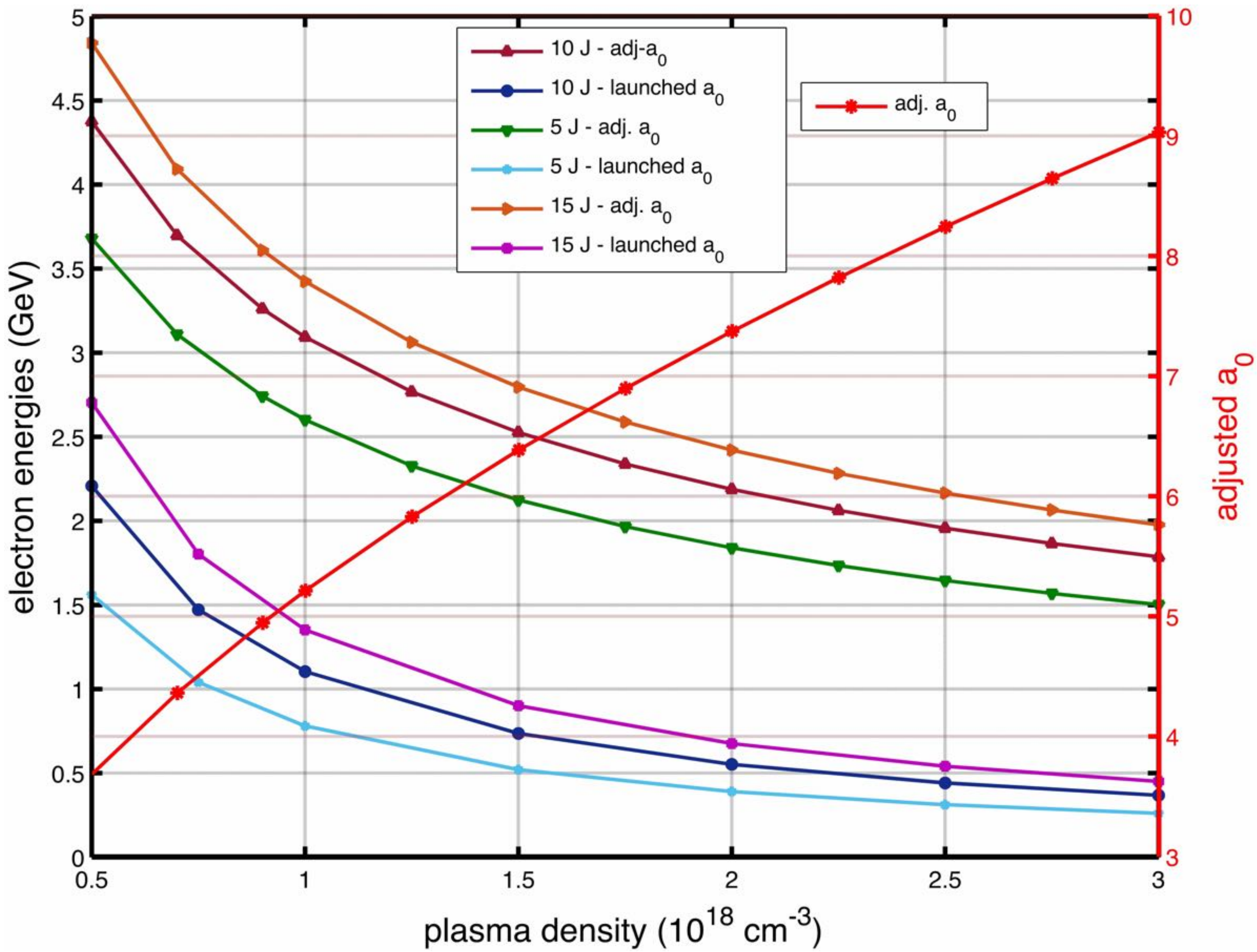
peak expt. $\Delta\mathcal{E}$: 800 MeV

$\Delta\mathcal{E}\ [\mathrm{a_0(adj)} = 8.3]$: 957 MeV

slightly better match to max electron energies

adjusted a_0 model

based on laser pulse envelope being squeezed to the matched spot-size



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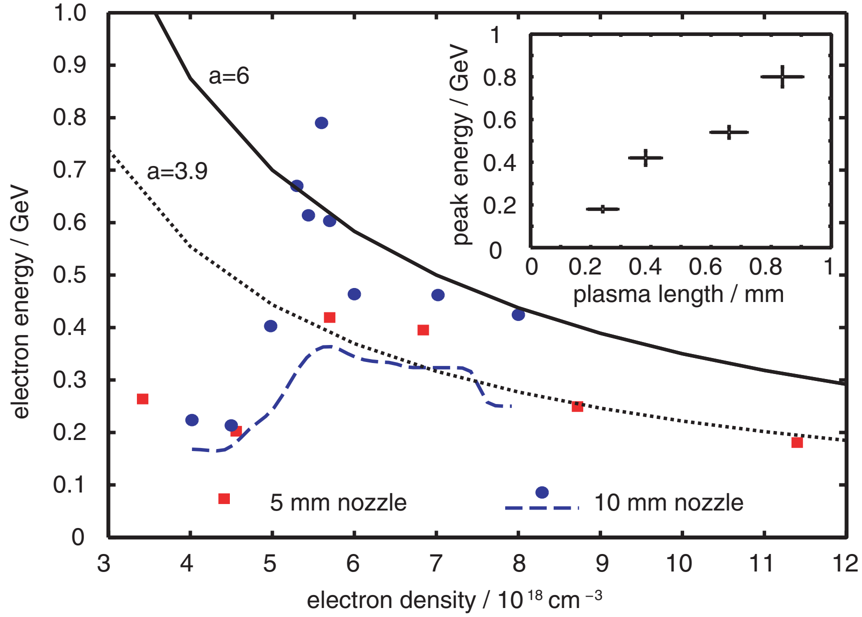
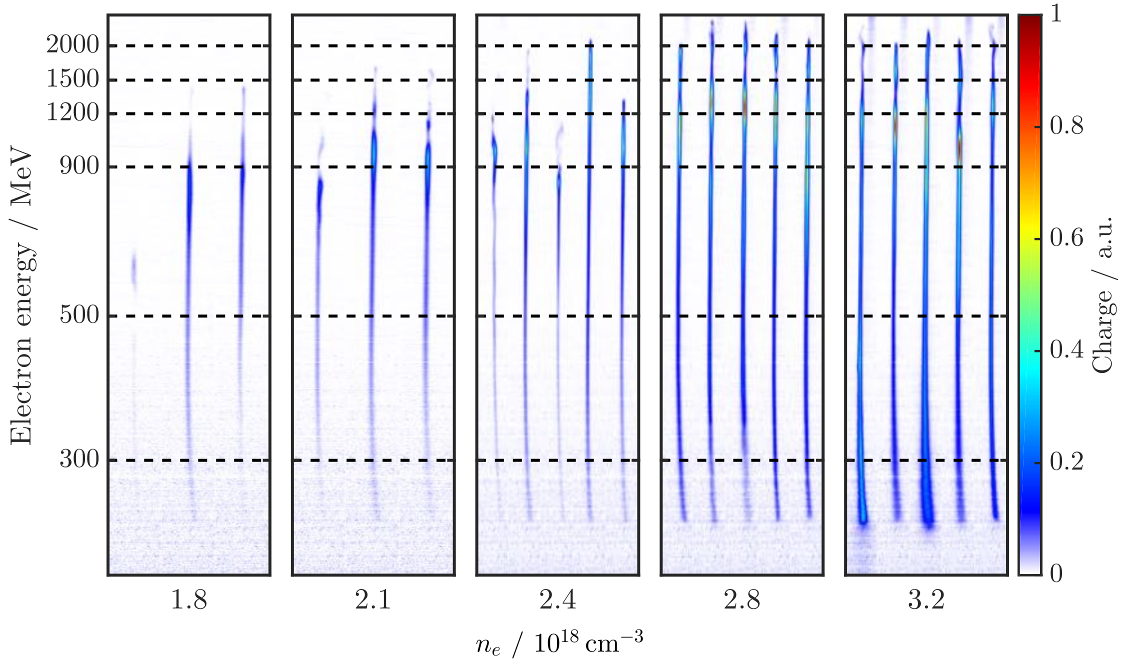
adjusted a_0 model

why is there an optimum density range over which the model predicts



2008 f/20 data



2015 f/40 data

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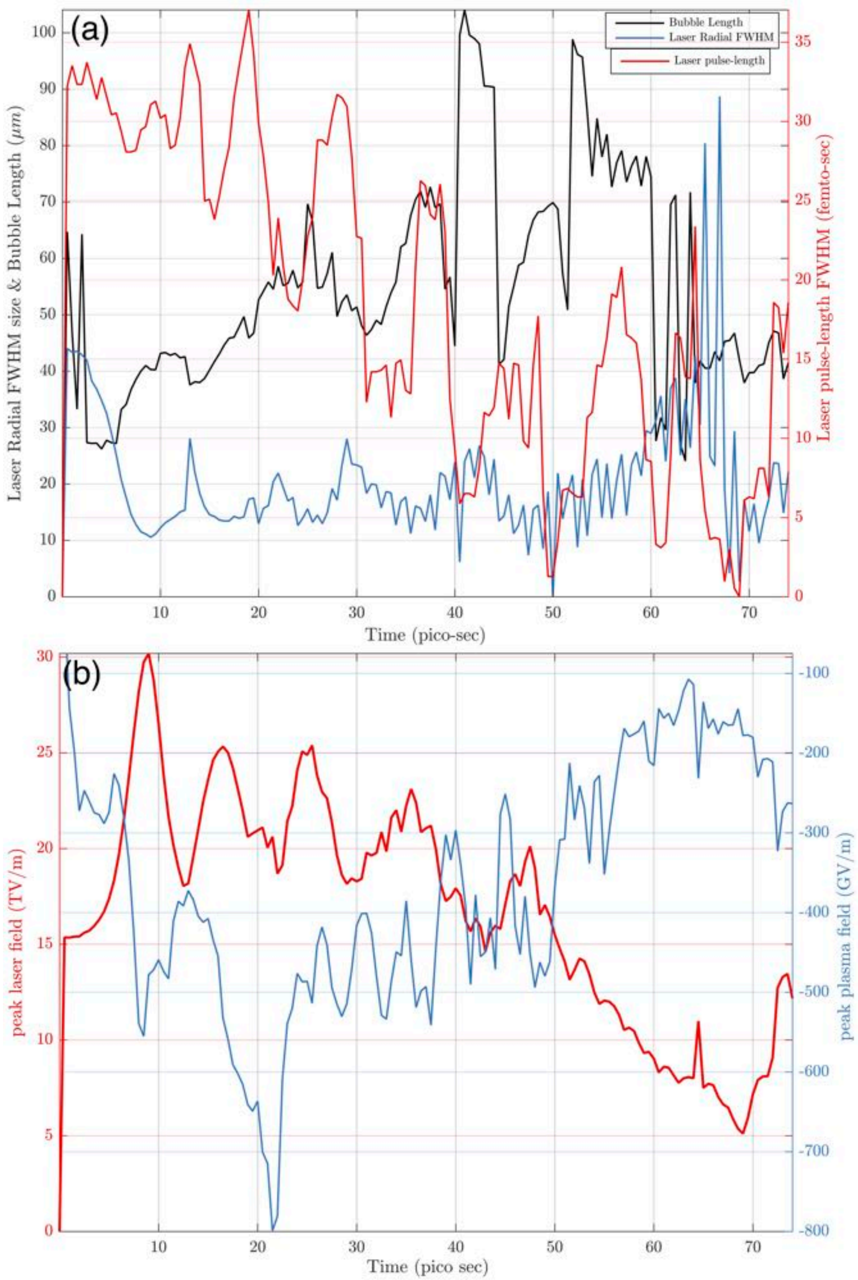
2D PIC simulations



- laser pulse radial envelope
  → oscillates around matched spot
- laser pulse temporal envelope
  → catastrophic events
- Bubble elongates more than
  → radial excursions
- Laser field → discrete surge events
- field surge → optical shock trigger
- optical shock state
  → long pond. F >> radial pond. F
- optical shock state
  → plasma field nearly TV/m
  → high-quality beam injection

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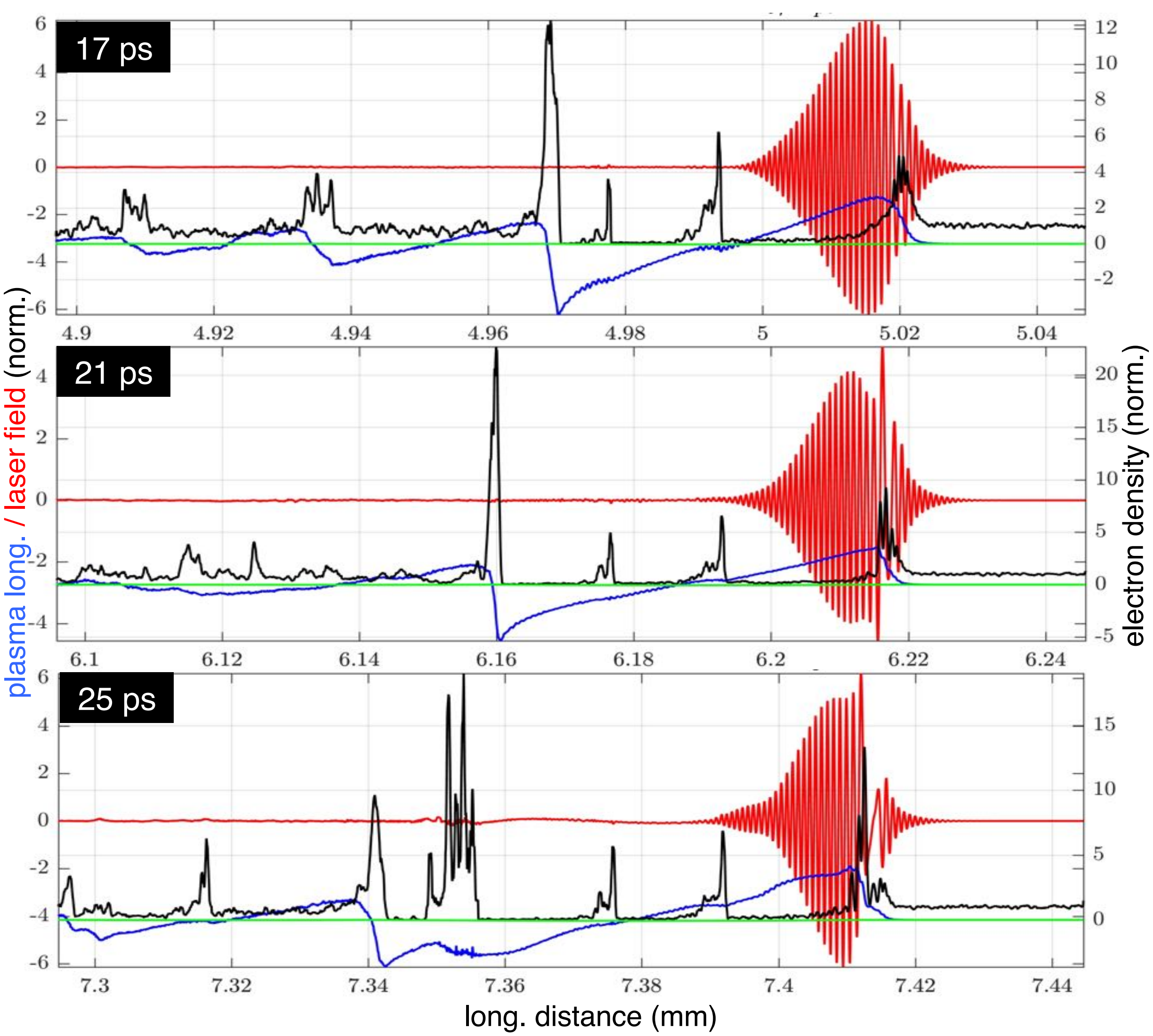
Optical shock excitation

each laser field surge event → optical shock excitation



localized laser velocities

$$\beta_g = \beta_{\phi-las}^{-1} \simeq \beta_{g0}\left[1 + \frac{1}{2\gamma_{g0}^2\beta_{g0}^2}\left(\langle a_\perp\rangle^2 - \frac{\delta n}{n_0}\right)\right]$$

$$\beta_{g0} = \sqrt{1 - \frac{\omega_{pe}^2}{\omega_0^2}}, \gamma_{g0} = \frac{\omega_0}{\omega_{pe}}$$

ZERO local group velocity

$$\beta_g(\xi, r) = 0$$

$$\frac{1}{2}\left(\frac{\delta n}{n_0} - \langle a_\perp\rangle^2\right) \simeq \frac{n_c}{n_0}$$

Local group velocity difference

Slice-up the laser pulse

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Dis-balanced Ponderomotive Forces

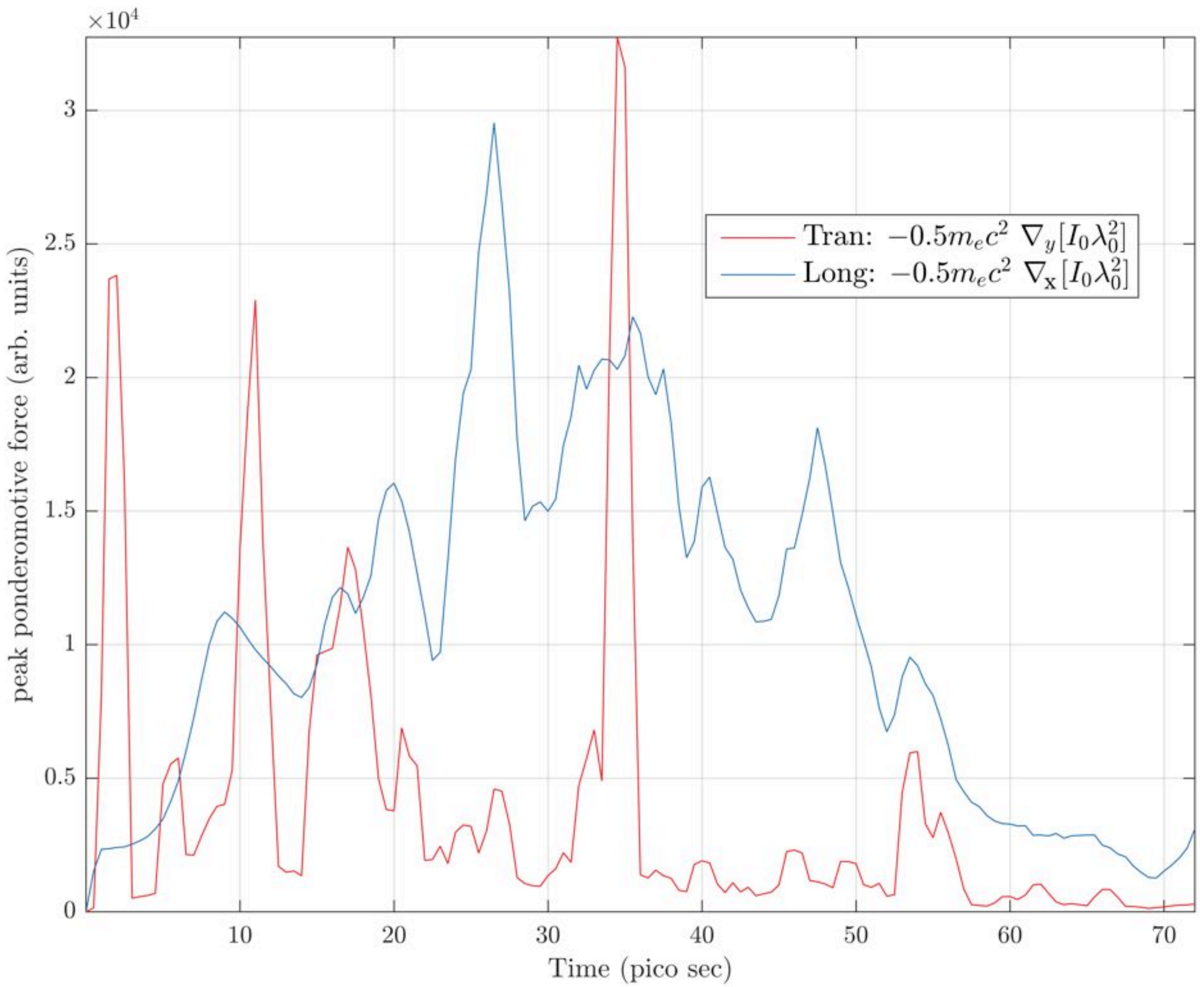
optical shock excitation → imbalanced pond. forces

$$\mathcal{E}^e_{quiv}(x,r) \propto I(x,r)\lambda_0^2(x,r)$$

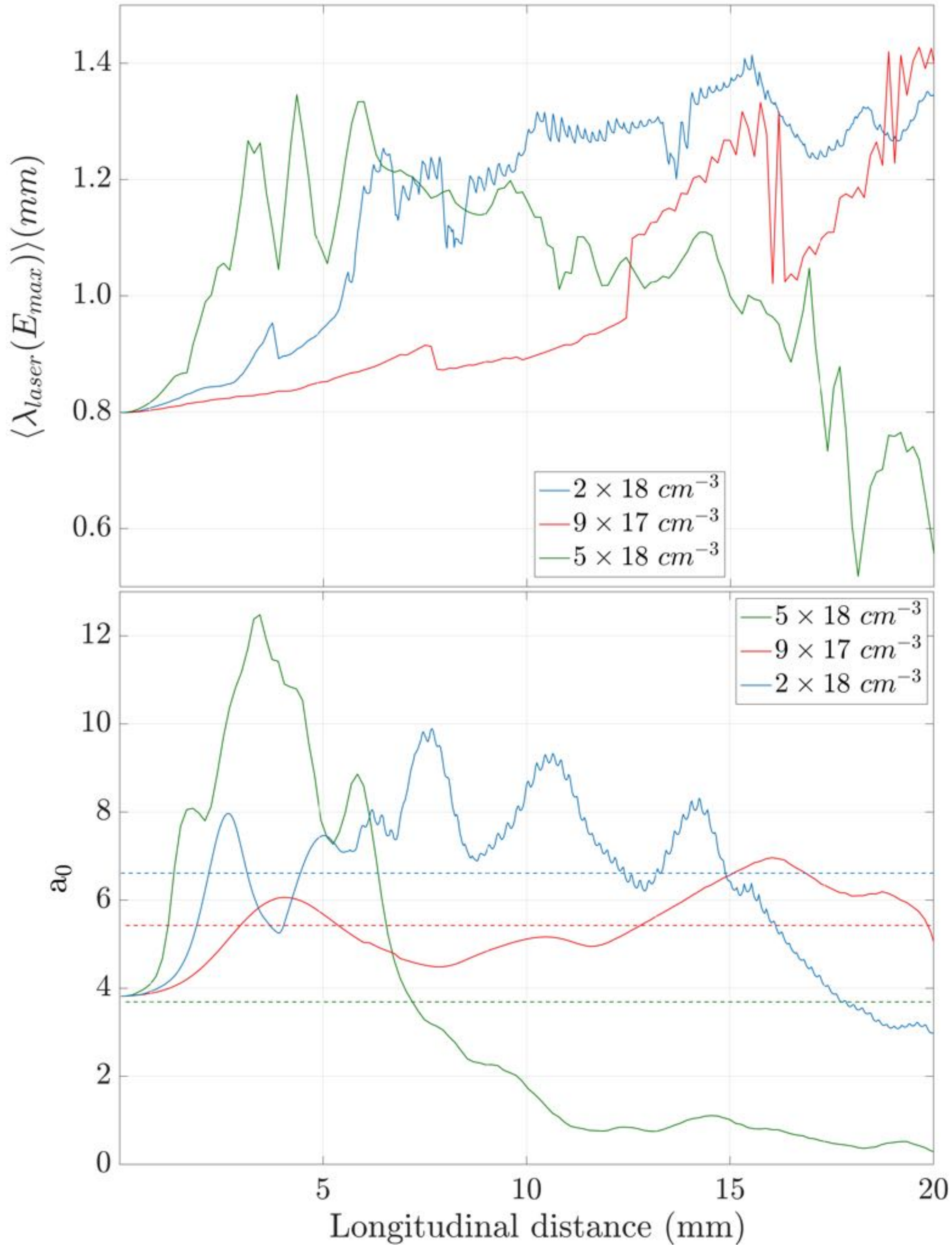
elongated bubble

$$\text{Spherical bubble}: \nabla_x \mathcal{E}^e_{quiv}(x,r) \simeq \nabla_r \mathcal{E}^e_{quiv}(x,r)$$

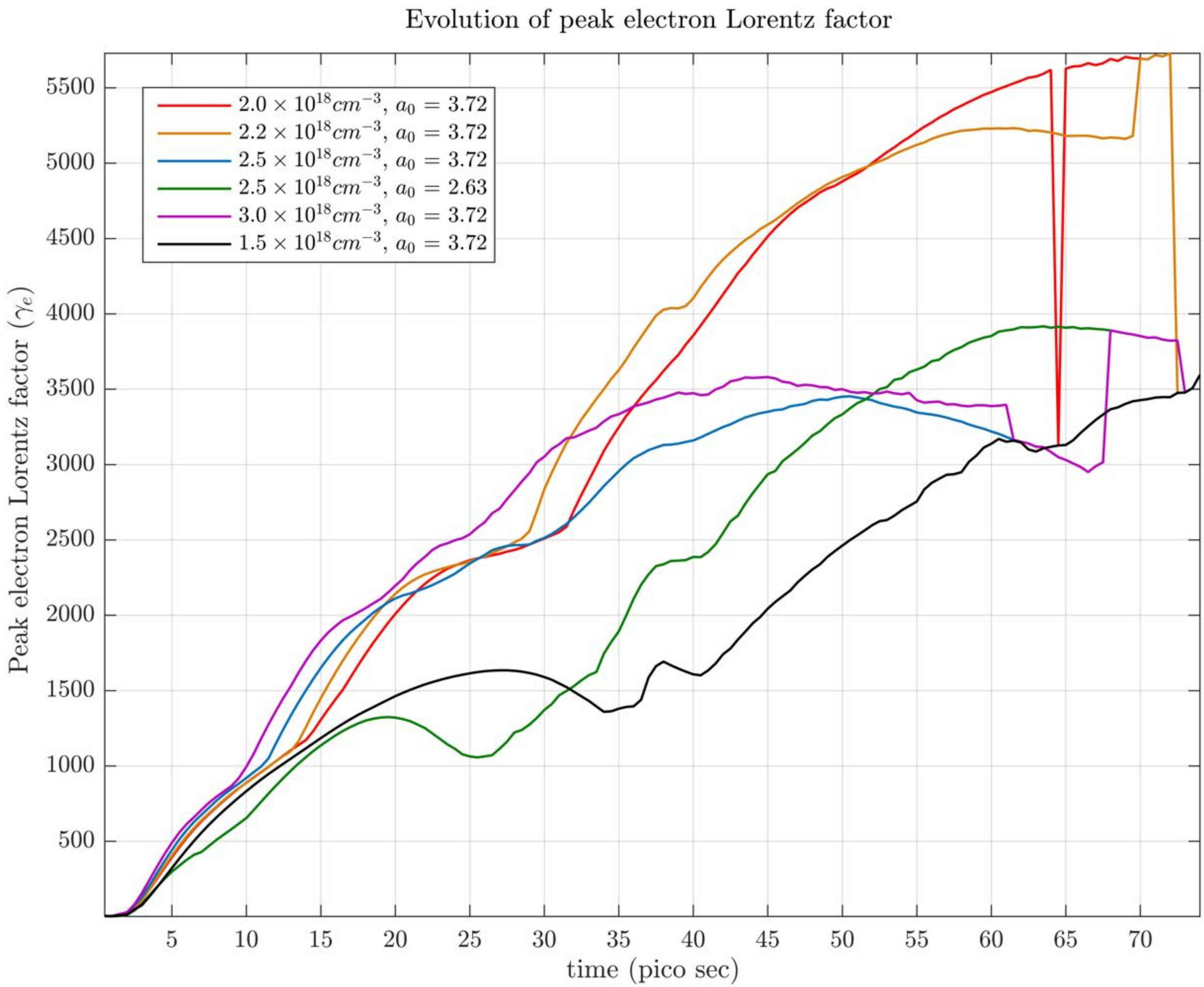
$$\text{Elongated bubble}: \nabla_x \mathcal{E}^e_{quiv}(x,r) \gg \nabla_r \mathcal{E}^e_{quiv}(x,r)$$



Wavelength and a_0



electron beam properties



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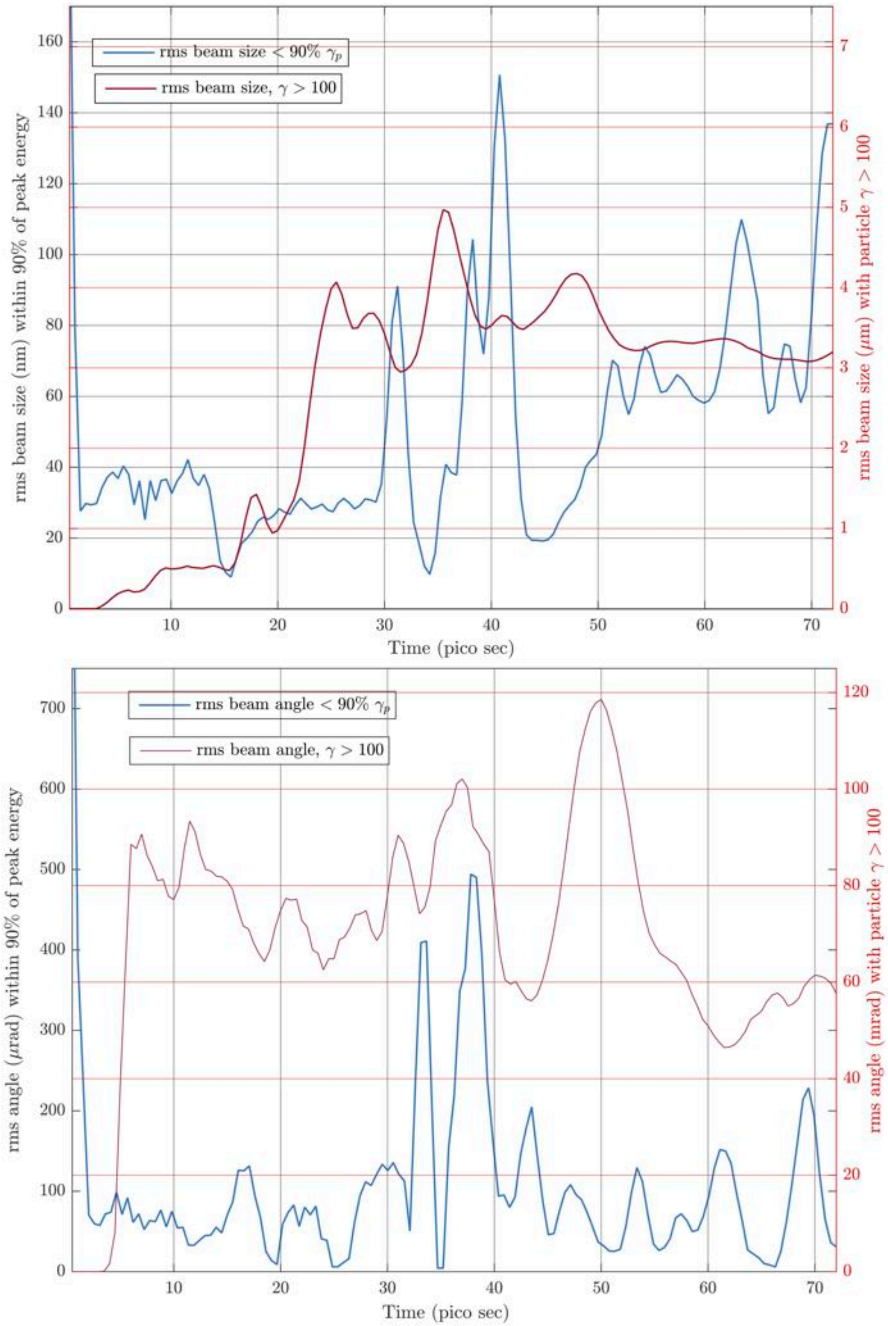
high-energy bunch quality



bunch transverse properties at ~ 2GeV
→ due to elongating bubble injection

→ rms transverse-size ~ 150 nm

→ rms angular-size ~ 100 μrad

→ geometric emittance ~ 10^{-5} mm-mrad

→ norm. emittance ~ 0.1 mm-mrad

→ beam exiting the plasma undergoes emittance reduction in exit ramp

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Summary

- matched spot-size – **NOT easy** to experimentally achieve Gaussian spot
- plasma-wave transverse profile distorted – due to laser hot-spots or non-uniformities – not good for sustained acceleration
- strongly mismatched regime – possible to achieve high-energy multi-GeV beams – here **peak-energy > 2GeV**
- Optical shock excitation – slicing up of the laser pulse due to its envelope dynamics
- elongated bubble – driven by optical shock state – high peak electric field and longer de-phasing lengths
- Injection scheme based on elongating bubble – high-quality bunch **emittance < 0.1 mm-mrad**
- mismatched regime – more injection events – **higher total efficiency** – laser to energetic particles