Staging of high-efficiency and high-quality laser-plasma accelerators for collider applications

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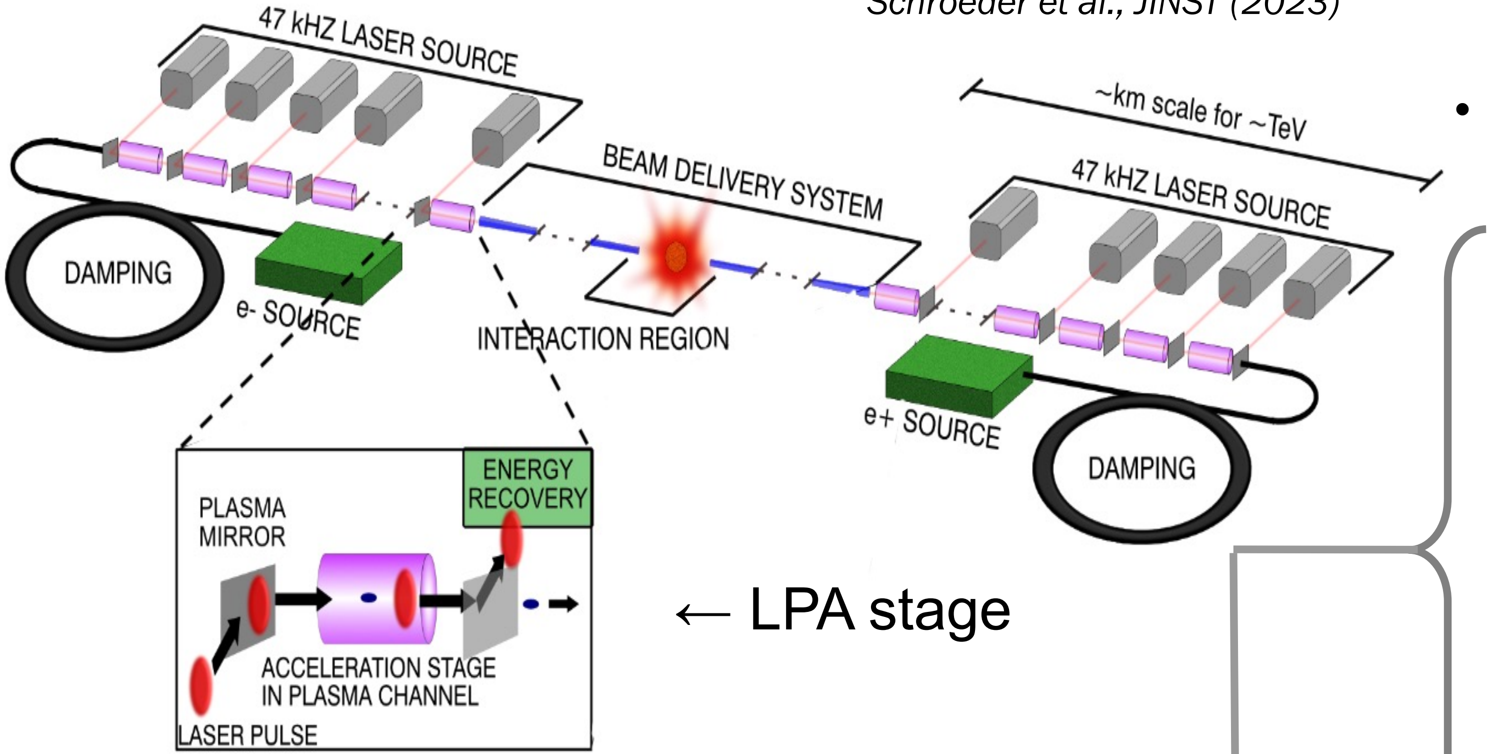
Conceptual design of a TeV-class LPA-based collider

Benedetti et al., arXiv (2022)
Schroeder et al., JINST (2023)



← LPA stage

- Setup based on <u>staging of LPAs</u> (high av. gradient → length <1 km/TeV)
- Minimization of wall-plug power and beam-strahlung + achieve desired luminosity:

→ n_0~10^{17} cm^{-3} → 10s of J laser / stage

→ multi-GeV energy gain / stage

→ high bunch charge (>100s pC)

→ high bunch quality (emittance < 0.1 um, energy spread < 1%)

→ high efficiency (10s %, laser → wake, wake → beam, …)

Schroeder et al., PRSTAB (2010)
Schroeder et al., NIMA (2016)

What type of LPA stage can best fulfill these requirements?
Can staging preserve the high bunch quality?

Conceptual design of a TeV-class LPA-based collider

Benedetti et al., arXiv (2022)
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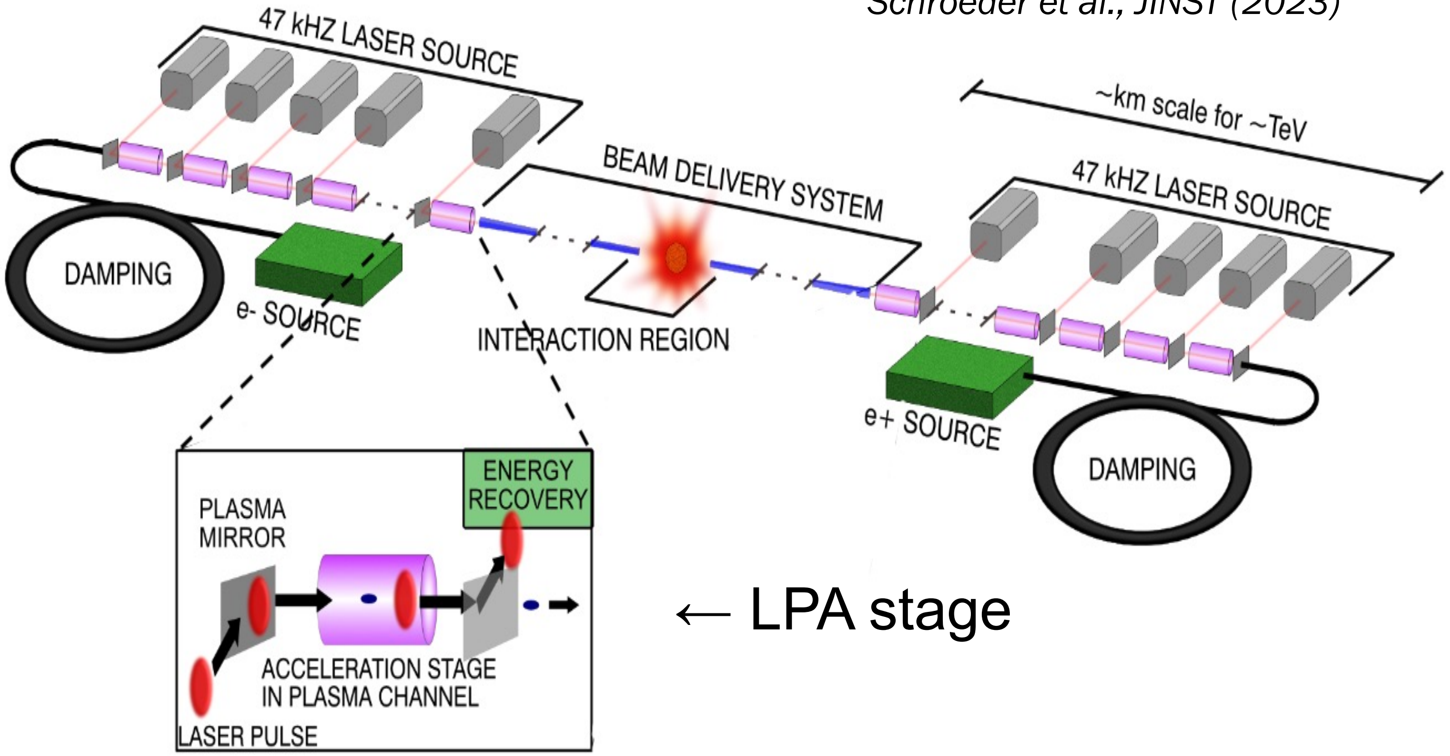

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  → high efficiency (10s %, laser → wake, wake → beam, …)

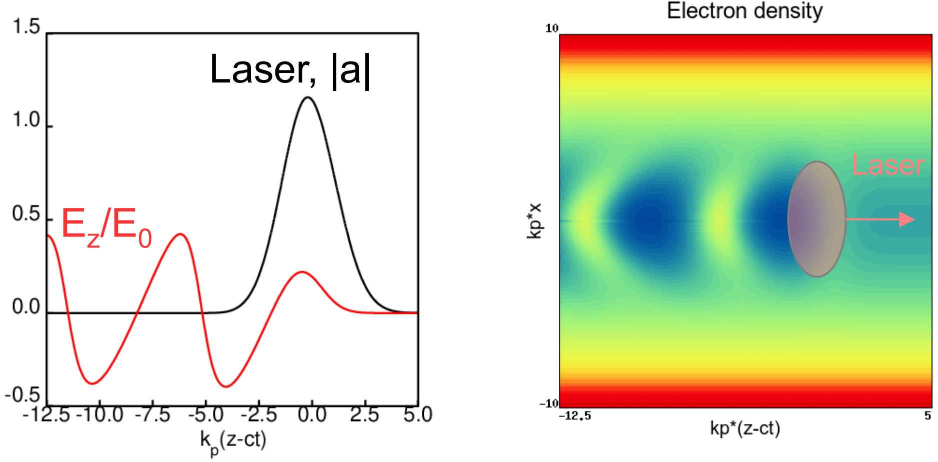
Schroeder et al., PRSTAB (2010)
Schroeder et al., NIMA (2016)

In this **talk**:

- Discuss **channel-guided** and **self-guided** LPA stages for **given (fixed) laser driver energy**
  → characterize max. energy gain, stage length, optimal bunch charge, etc.;
- Present examples of **channel-guided** and **self-guided** LPA stages relevant for **collider applications**
  → discuss **bunch quality** preservation during **staging**

Channel-guided and self-guided LPAs driven by a laser with given (fixed) energy operate at different plasma densities

Channel-guided LPA



Laser driver: $a_0 \sim 1$, $k_p w_0 \sim 3$, $k_p L \sim 1$ (~resonant)

→ **Guiding provided** by **plasma channel** ($P/P_c \sim 1$)

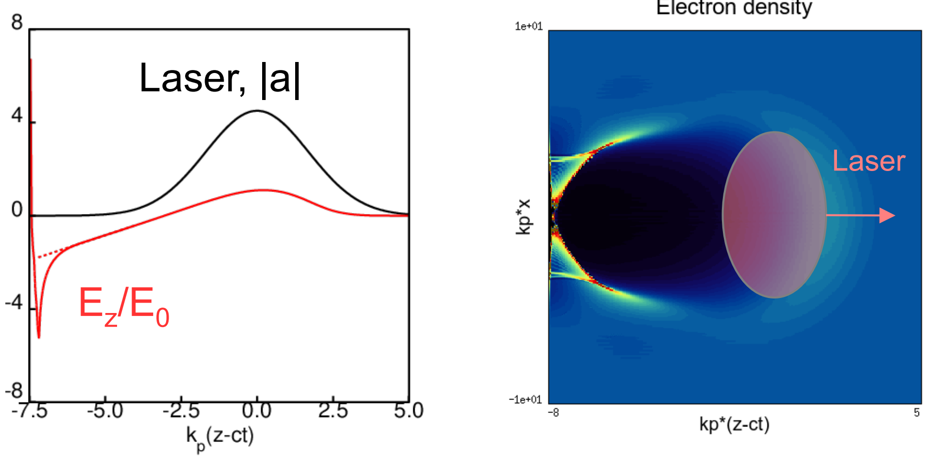
→ Operates best in quasi-linear regime ($a_0 <\sim 3$), nonlinear possible

→ Fixing normalized laser parameters, wavelength, and laser energy determines on-axis density:

$$n_0 \propto \frac{a_0^{4/3}(k_p w_0)^{4/3}(k_p L)^{2/3}}{\lambda_0^{4/3} U_0^{2/3}}$$

(**n_0=1.2x10^{17} cm^{-3}** for U=10 J, λ_0=0.8 μm, a_0=1.5, $k_p w_0$= 3, $k_p L$=1)

Self-guided LPA



Lu et al., PR ST-AB (2007)

Laser driver*: $a_0 \sim 4.5$, $k_p w_0 = 2\sqrt{a_0}$, $L_{fwhm} = (2/3) w_0$

→ **Self-guiding** ($P/P_c >> 1$)

→ Operates in nonlinear regime

→ Fixing laser strength, wavelength, and laser energy determines density:

$$n_0 \propto \frac{a_0^{7/3}}{\lambda_0^{4/3} U_0^{2/3}}$$

(**n_0=1.5x10^{18} cm^{-3}** for U=10 J, λ_0=0.8 μm, a_0=4.5)

Energy gain: $\Delta W_{\mathrm{bunch}} \sim n_0^{-1}$

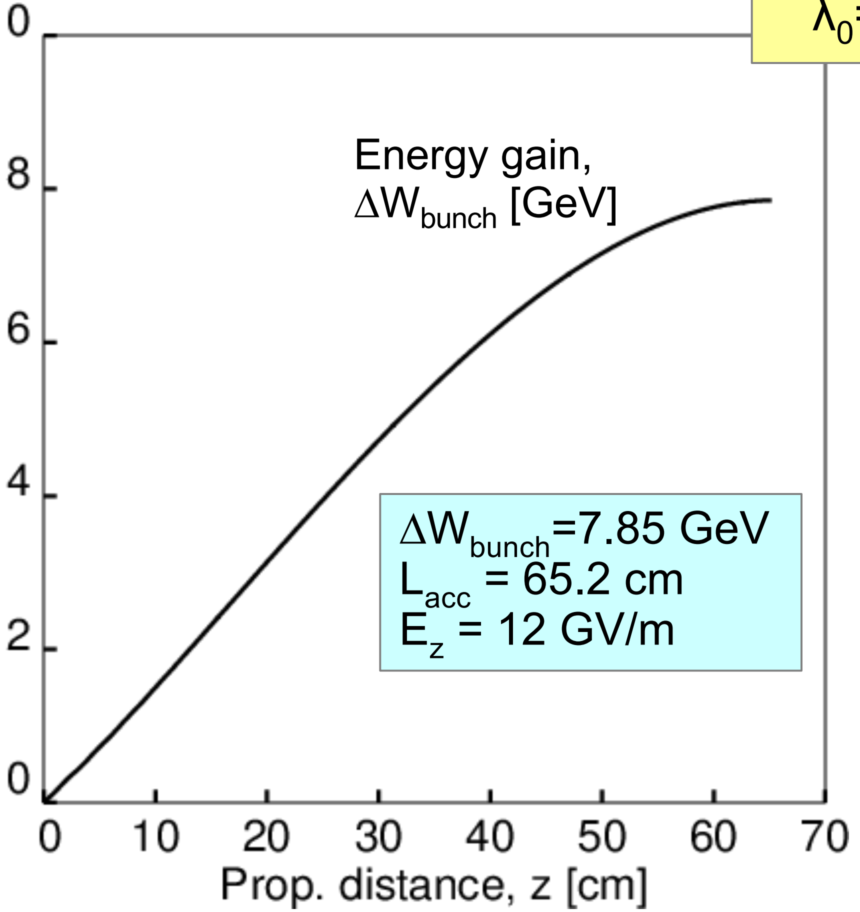
→ Energy gain in channel-guided LPAs **larger** than for self-guided LPAs owing to **much lower density of operation**
(which compensates for the larger gradients available in self-guided stages)

For given (fixed) laser energy the max energy gain in channel-guided LPAs is larger than in self-guided LPAs (negligible beamloading and short bunches assumed)

Laser driver:
U=10 J,
λ_0=0.8 μm

Channel-guided LPA (quasi-linear regime)

$n_0=1.05\times10^{17}$ cm^{-3}
$a_0=1.9$
$k_pL=0.5$
$k_0w=3$
Symmetric driver
NO tapering

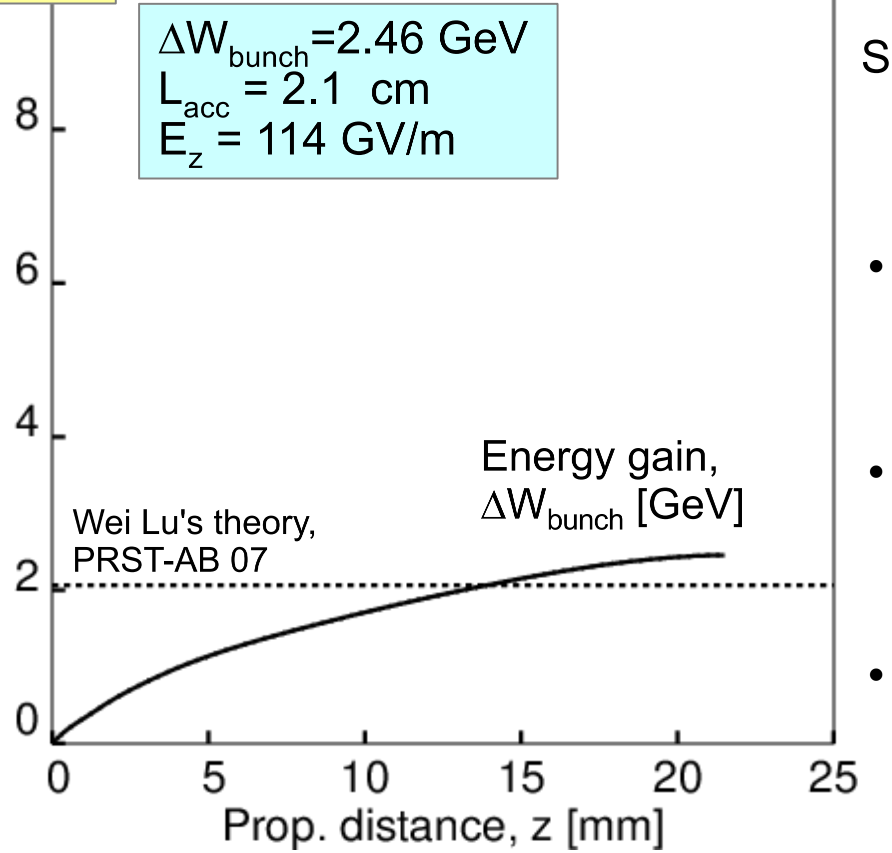


ΔW_{bunch}=7.85 GeV
L_{acc} = 65.2 cm
E_z = 12 GV/m

- Energy gain <u>maximized</u> exploring:
  $0.5 \leq a_0 \leq 2.5$,
  $0.2 \leq k_pL \leq 2$,
  $2 \leq k_0w \leq 5$
- We require:
  $E_z > 10$ GV/m

Self-guided LPA (nonlinear / bubble regime)

$n_0=1.14\times10^{18}$ cm^{-3}
$a_0=4.0$
Symmetric driver
NO tapering



ΔW_{bunch}=2.46 GeV
L_{acc} = 2.1 cm
E_z = 114 GV/m

- Energy gain maximized for $a_0 \approx 4 - 4.5$
- For $a_0 < 4$ insufficient self-guiding
- For $a_0 > 4.5$ significant laser evolution

→ Energy gain in channel-guided LPAs can be >3 times larger than in self-guided LPAs

→ Scaling laws: $\Delta W_{bunch} \sim U^{2/3} \lambda_0^{-2/3}$ – $L_{acc} \sim U$

C. Benedetti, in preparation

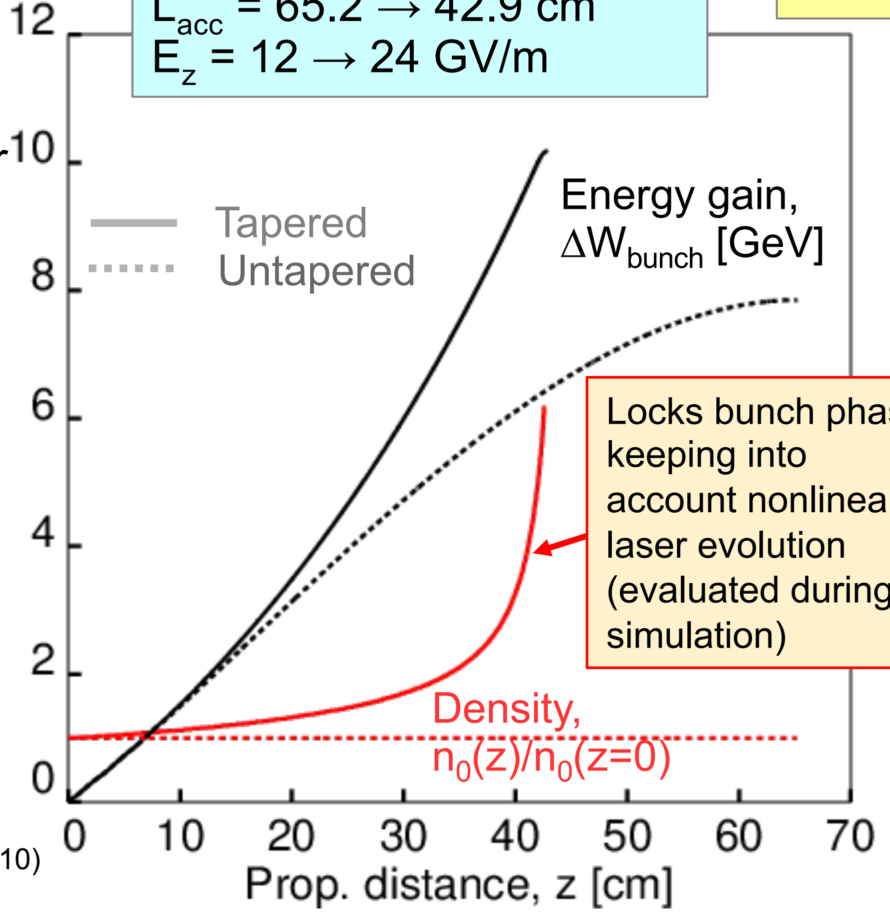
Energy gain in quasi-linear channel-guided stages can be increased with optimal (includes laser evolution effects) longitudinal density tapering

Laser driver:
U=10 J,
λ_0=0.8 μm

Channel-guided LPA (quasi-linear regime)

$n_0=1.05\times10^{17}$ cm^{-3}
$a_0=1.9$
$k_pL=0.5$
$k_0w=3$
Symmetric driver

ΔW_{bunch}=7.85 → 10.2 GeV
L_{acc} = 65.2 → 42.9 cm
E_z = 12 → 24 GV/m

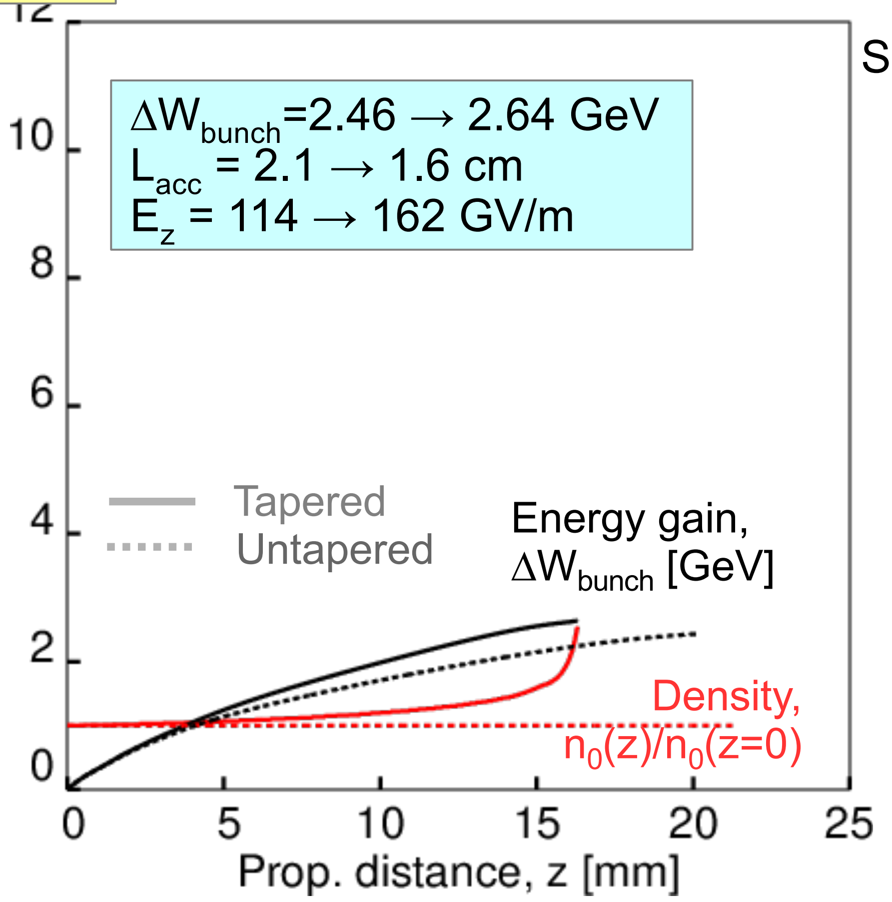


Locks bunch phase keeping into account nonlinear laser evolution (evaluated during simulation)

Self-guided LPA (nonlinear / bubble regime)

$n_0=1.14\times10^{18}$ cm^{-3}
$a_0=4.0$
Symmetric driver

ΔW_{bunch}=2.46 → 2.64 GeV
L_{acc} = 2.1 → 1.6 cm
E_z = 114 → 162 GV/m



A. Pukhov, PRE (2008)
P.Tomassini, Qfluid code
W. Rittershofer, POP (2010)

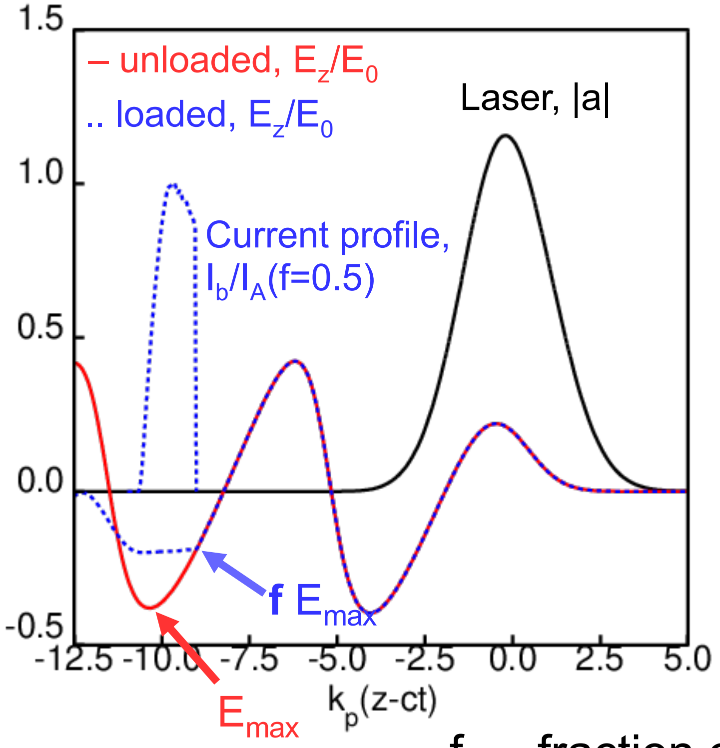
→ Energy gain in channel-guided LPAs can be ~4 times larger than in self-guided LPAs w/ tapering

→ Density tapering more effective for channel-guided/quasi-linear stages than for self-guided/nonlinear stages

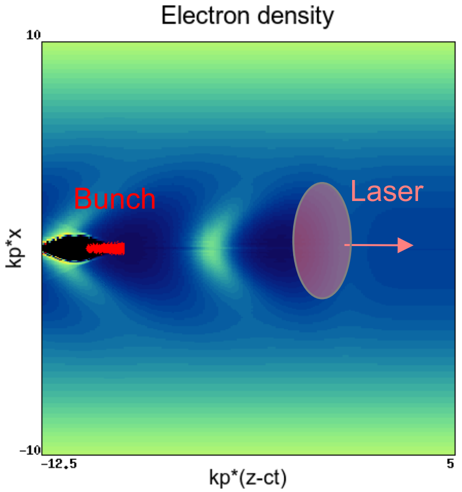
Determining characteristic charge that can be accelerated in an LPA requires identifying bunch profile that flattens the wake (i.e., absorbs energy from the wake)

Characteristic charge ←→ current profile that flattens the wakefield within the bunch (i.e., absorbs wake's energy)

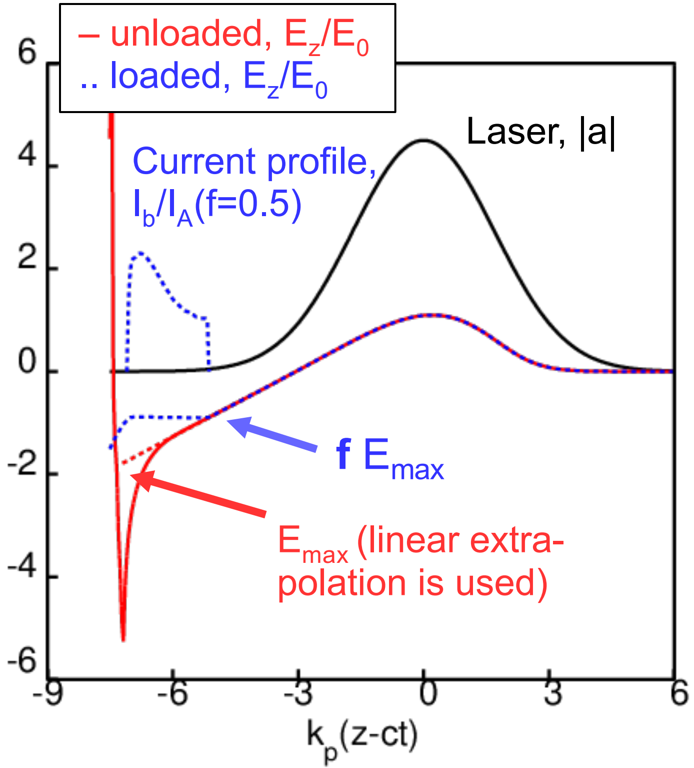
Channel-guided LPA (quasi-linear regime)



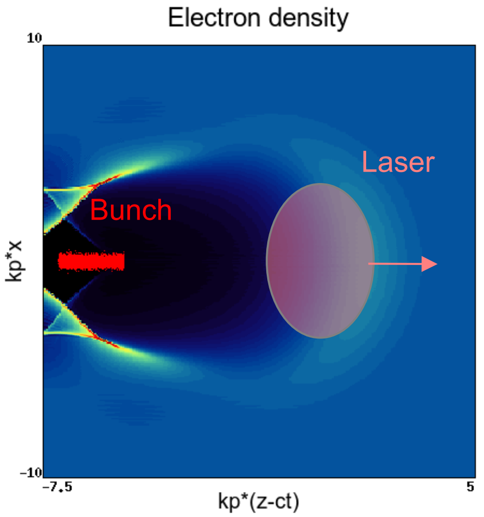
$a_0=1$, $k_pw_0=4$, $k_pL=1.8$



Self-guided (nonlinear / bubble regime)



$a_0=4.5$



f → fraction of the max accelerating field (E_{max}) experienced by the bunch

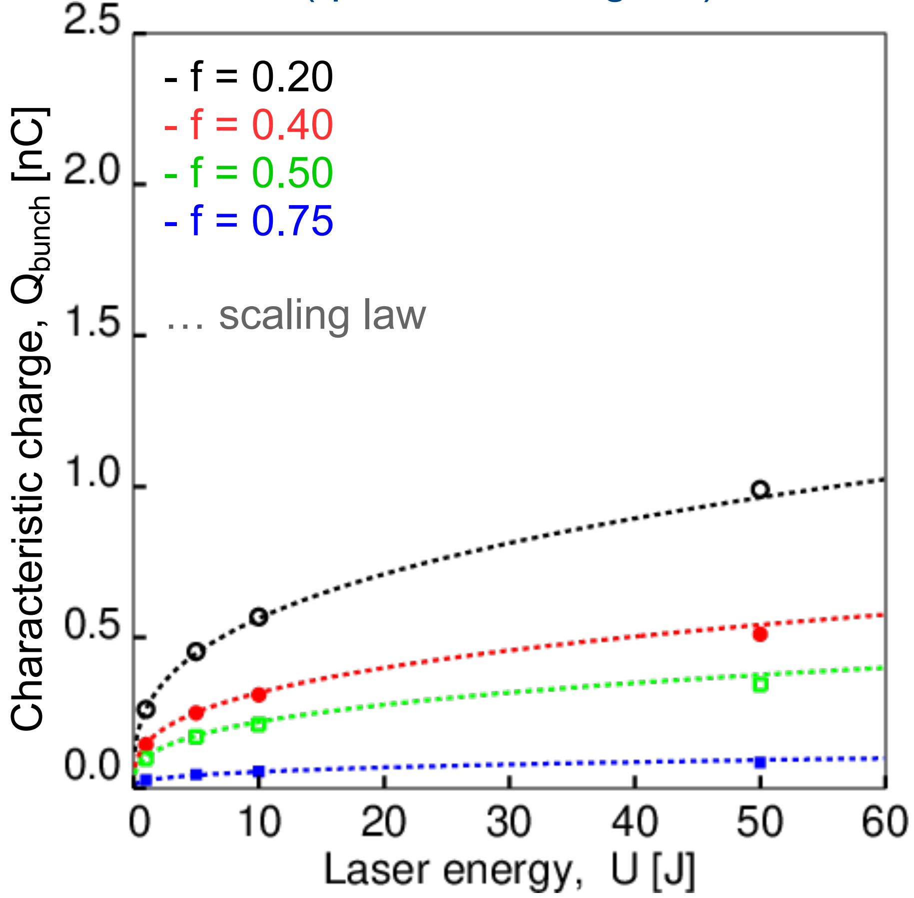
- Linear regime (i.e., $E_z/E_0 \ll 1$) → triangular profile (Katsouleas et al., Part. Accel., 1987)
- Blowout regime (requires $\delta n \sim n_0$, i.e., $a_0 > 8\text{-}10$) → trapezoidal profile (Tzoufras et al., PRL, 2009)

→ Characteristic current profile depends on the LPA regime and can be computed numerically

For given laser energy the characteristic bunch charge accelerated in self-guided LPAs is larger than in channel-guided LPAs

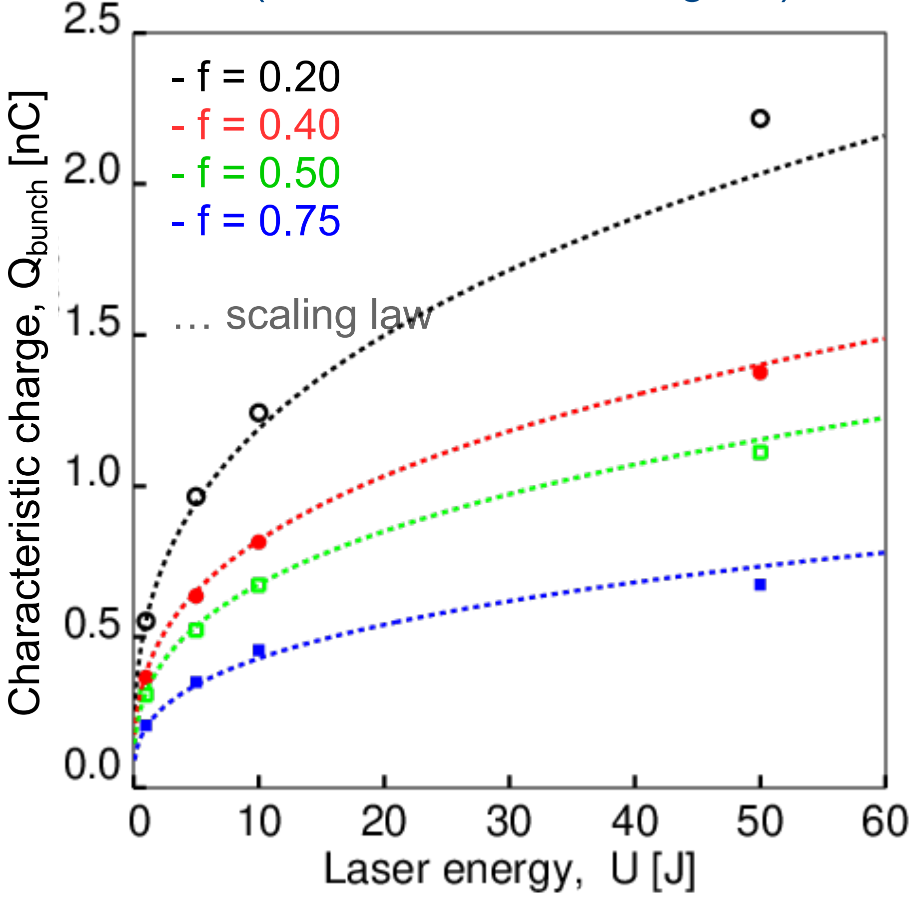
a_0=1.6, $k_p w_0$=4, $k_p L$=1.8, λ_0=0.8 µm

Channel-guided LPA
(quasi-linear regime)



Self-guided LPA
(nonlinear / bubble regime)

a_0=4.5, λ_0=0.8 µm

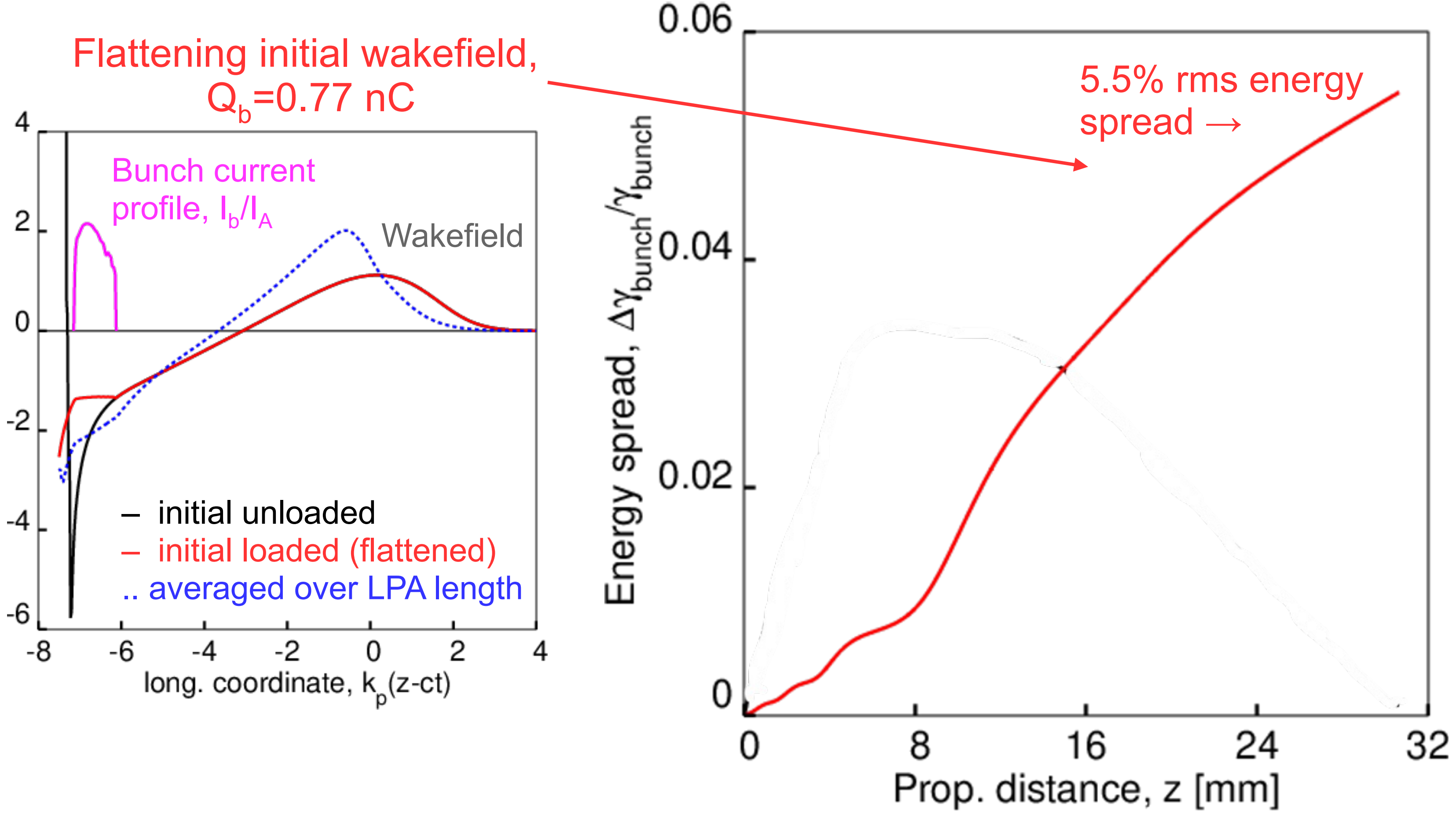


Scaling of the accelerated charge: $Q_{bunch}(U, \lambda_0) \sim U^{1/3} \lambda_0^{2/3}$

→ Charge in self-guided LPAs is >2-8 times larger than for channel-guided LPAs (owing to larger acc. gradient)

Production of beams with a small energy spread requires flattening the wakefield AVERAGED over the LPA length

Self-guided LPA (bubble/nonlinear): U=50 J [a_0=4.5, λ_0=0.8 μm], f=0.75



Flattening initial wakefield, Q_b=0.77 nC

5.5% rms energy spread →

- Current profile that flattens initial wake not optimal to minimize energy spread
  → bunch acquires energy chirp (= energy spread) because of laser evolution

Production of beams with a small energy spread requires flattening the wakefield AVERAGED over the LPA length

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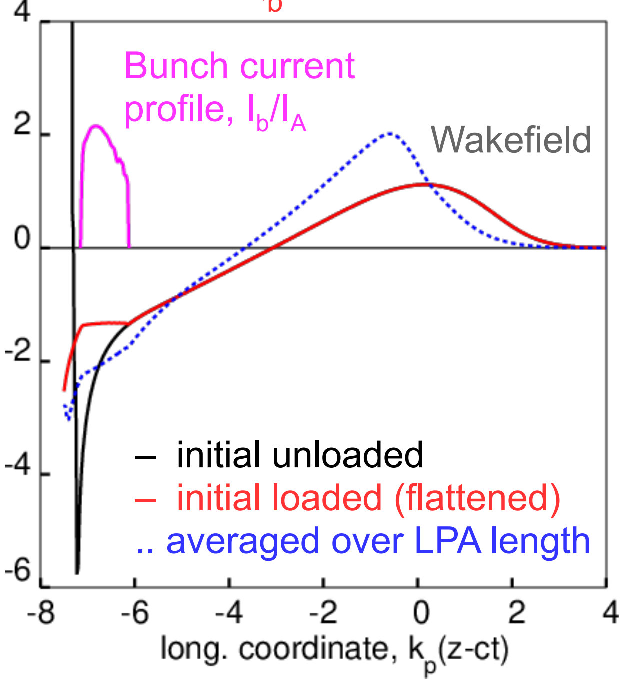
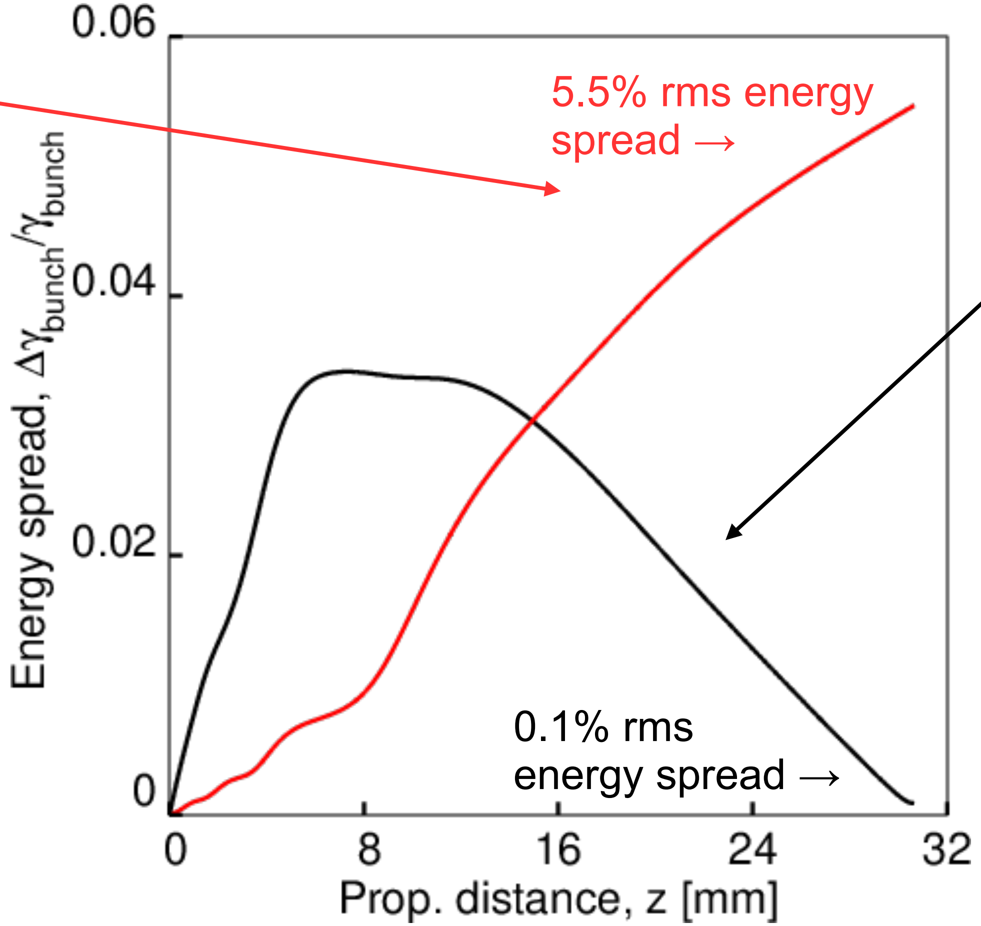
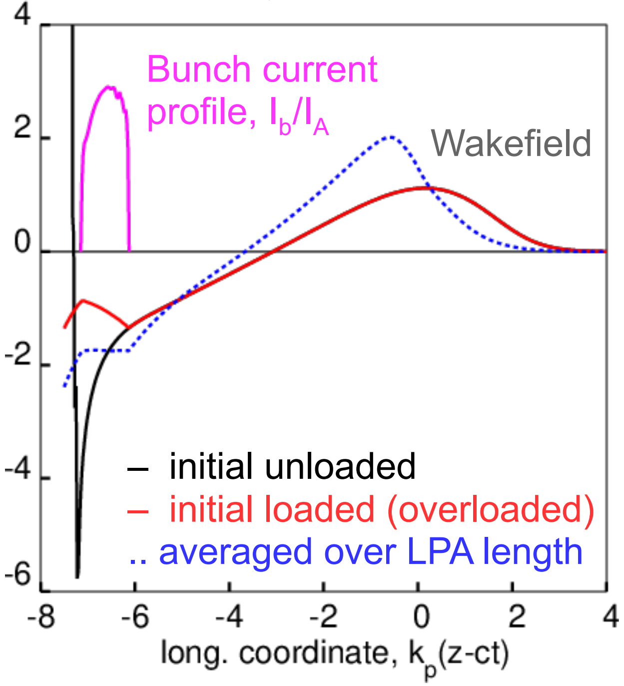




5.5% rms energy spread →

0.1% rms energy spread →

Flattening average wakefield, Q_b=1.09 nC



- Current profile that flattens initial wake not optimal to minimize energy spread
  → bunch acquires energy chirp (= energy spread) because of laser evolution
- Optimal beam profile: energy chirp imparted initially (overloading) compensated during acceleration
  → minimum energy spread achieved at the end of the stage

A self-guided stage operating in the bubble regime providing high-gradient, high-charge, and high-efficiency acceleration has been designed

Laser: U=50 J, λ_0=1.0 μm, a_0=4.5, T_0=80 fs, w_0=36 μm
Plasma: n_0= 3.4x10^{17} cm^{-3}, stage length = 3.1 cm, linear taper (+74%)

ΔW_{bunch}= 3.08 GeV (100 GV/m)
Q_{bunch}= 1.3 nC – L_{bunch} =9.3 μm – I_{bunch} =49 kA
Energy spread = 0.1%

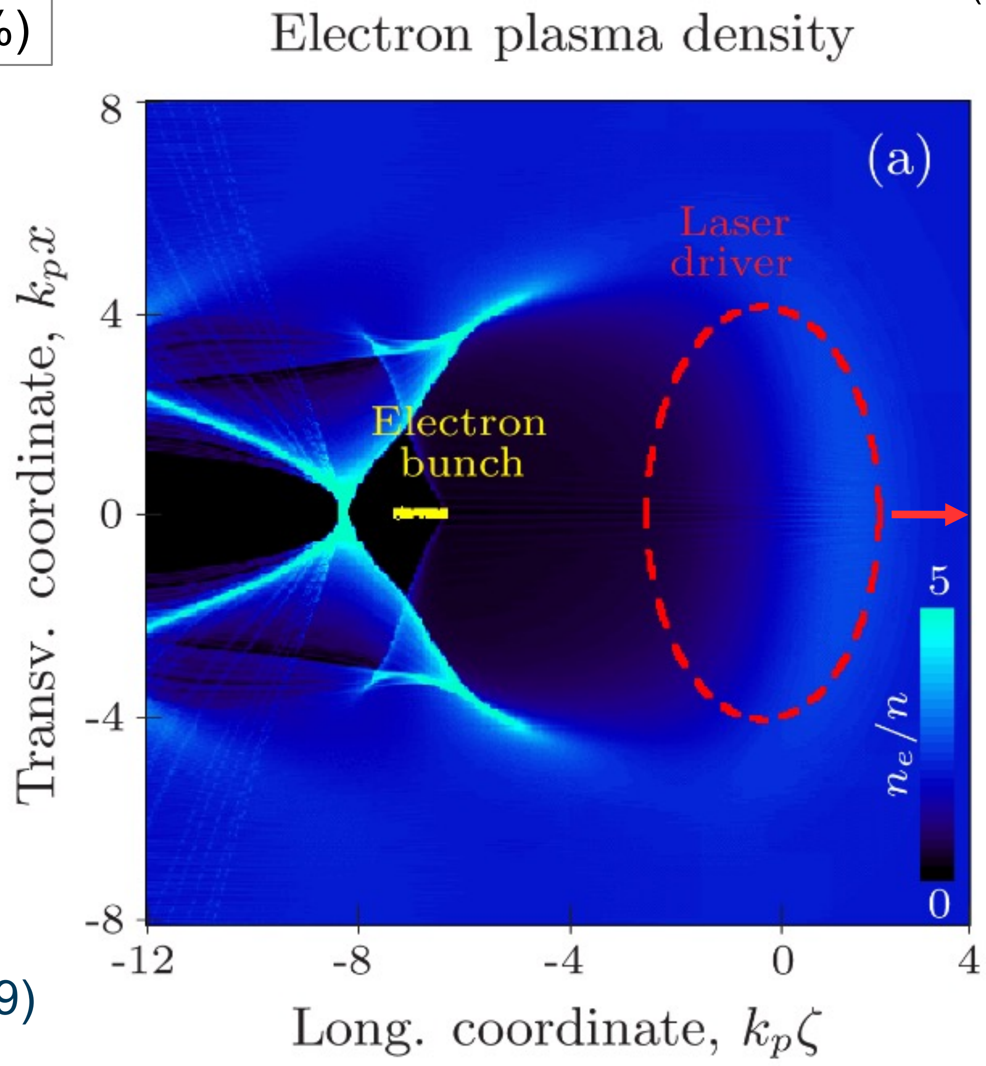
Energy considerations:

- Wake-to-bunch energy transfer = 40%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic

→ TeV-class linac → cascading a few 100s of LPA stages

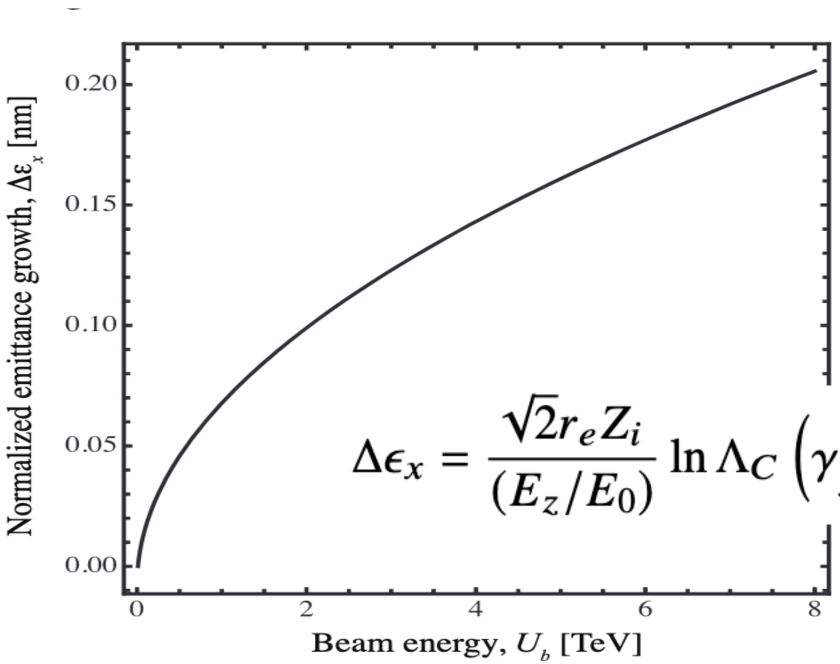
→ Not suitable for positron acceleration (different acceleration scheme required for positron arm, e.g., Diederichs et al., PRAB 2019)

Schroeder et al., JINST (2022)



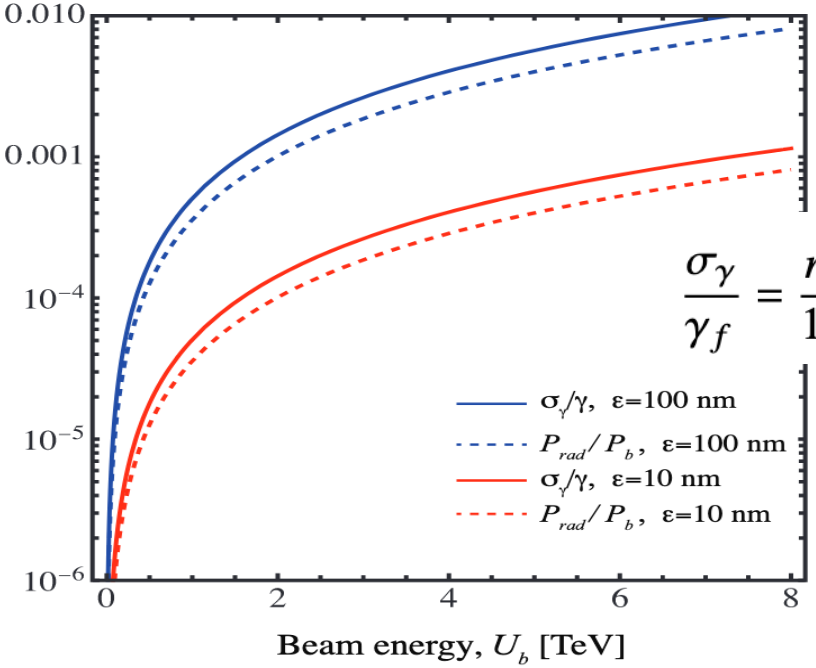
LPA stage in the bubble regime provides quality-preserving acceleration

- **Coulomb scattering**: emittance growth from collisions with background ions (Hydrogen) is < nm for multi-TeV beams owing to strong focusing provided by bubble wake.



$$\Delta\epsilon_x = \frac{\sqrt{2}r_e Z_i}{(E_z/E_0)} \ln\Lambda_C \left(\gamma_f^{1/2} - \gamma_i^{1/2}\right)$$

- **Betatron radiation**: for low emittance beams the synchrotron radiation-induced energy spread and power loss are < 1%.



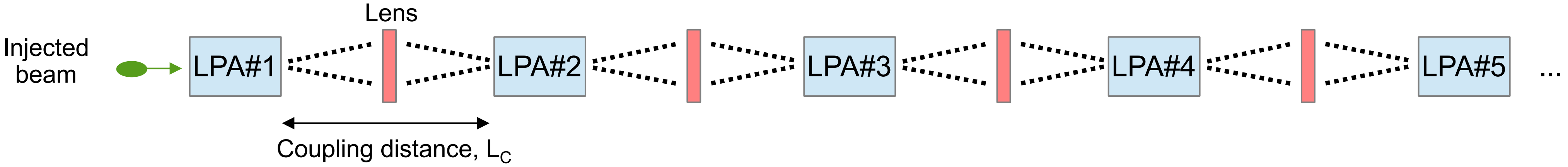
$$\frac{\sigma_\gamma}{\gamma_f} = \frac{r_e}{15} \frac{k_p^2 \gamma_f^{3/2} (\epsilon_x + \epsilon_y)}{(E_z/E_0)}$$

- **Transverse beam stability**:
  → beam hosing suppressed by spread in betatron frequency induced by background ion motion triggered by the high-charge, low-emittance, and high-energy beam;

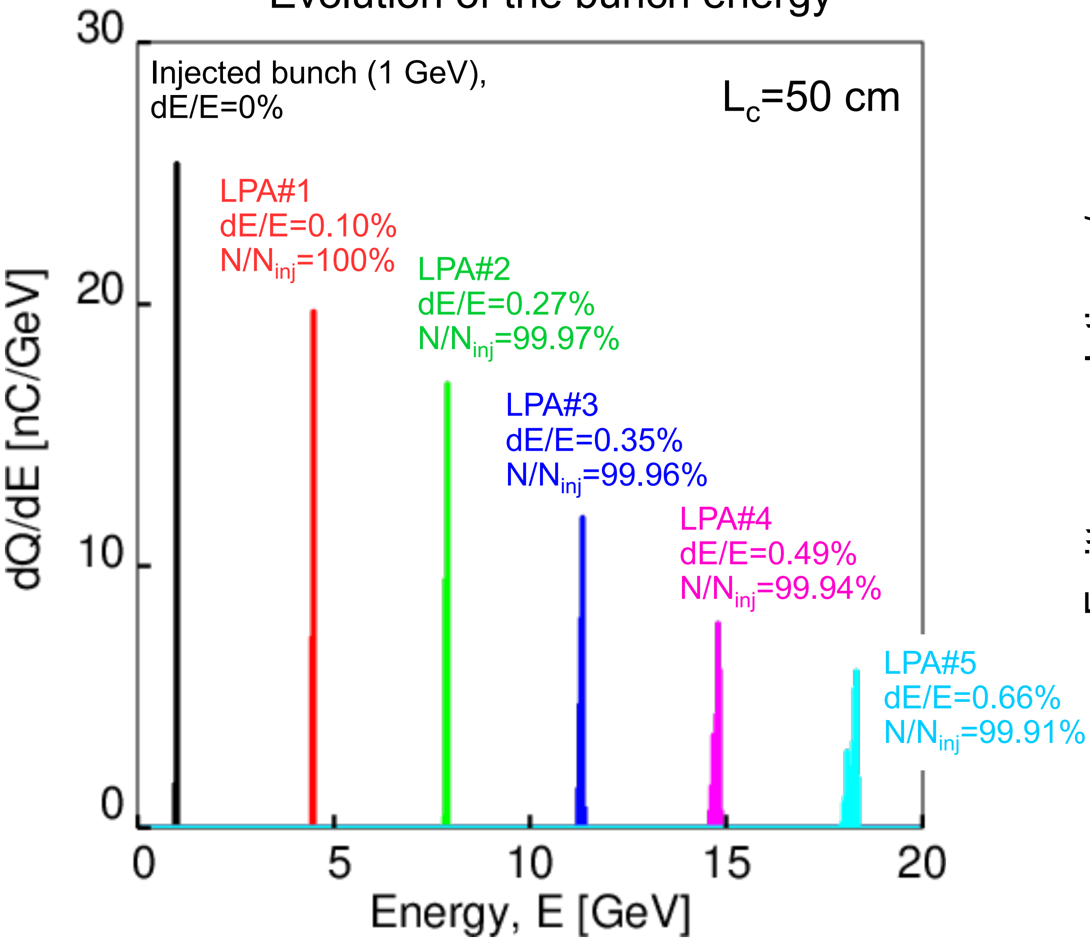
  → beam emittance from ion motion suppressed by bunch tapering (nonlinear matching).

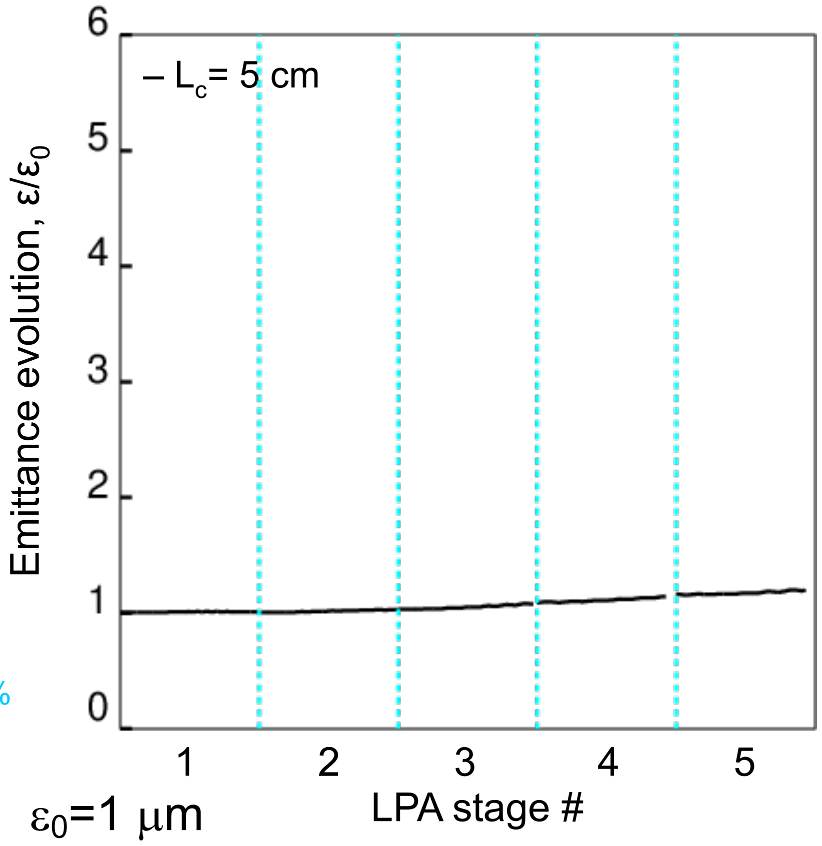
Mehrling et al., PRL (2018)
Benedetti et al, PRAB (2017)
Benedetti et al., Phys. Plasmas (2021)

Emittance preservation requires development of achromatic inter-stage transport elements for e-beam.

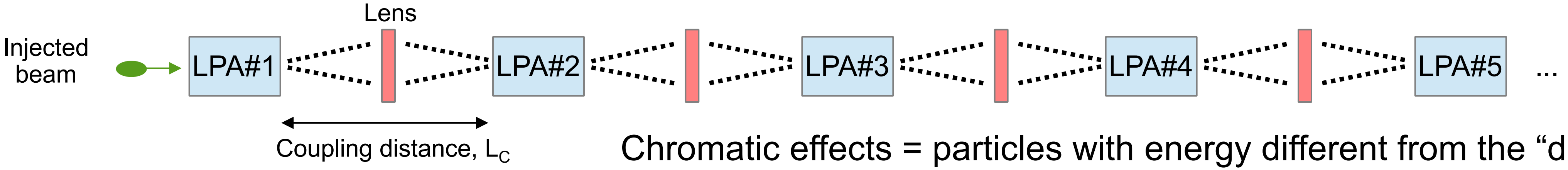


Evolution of the bunch energy



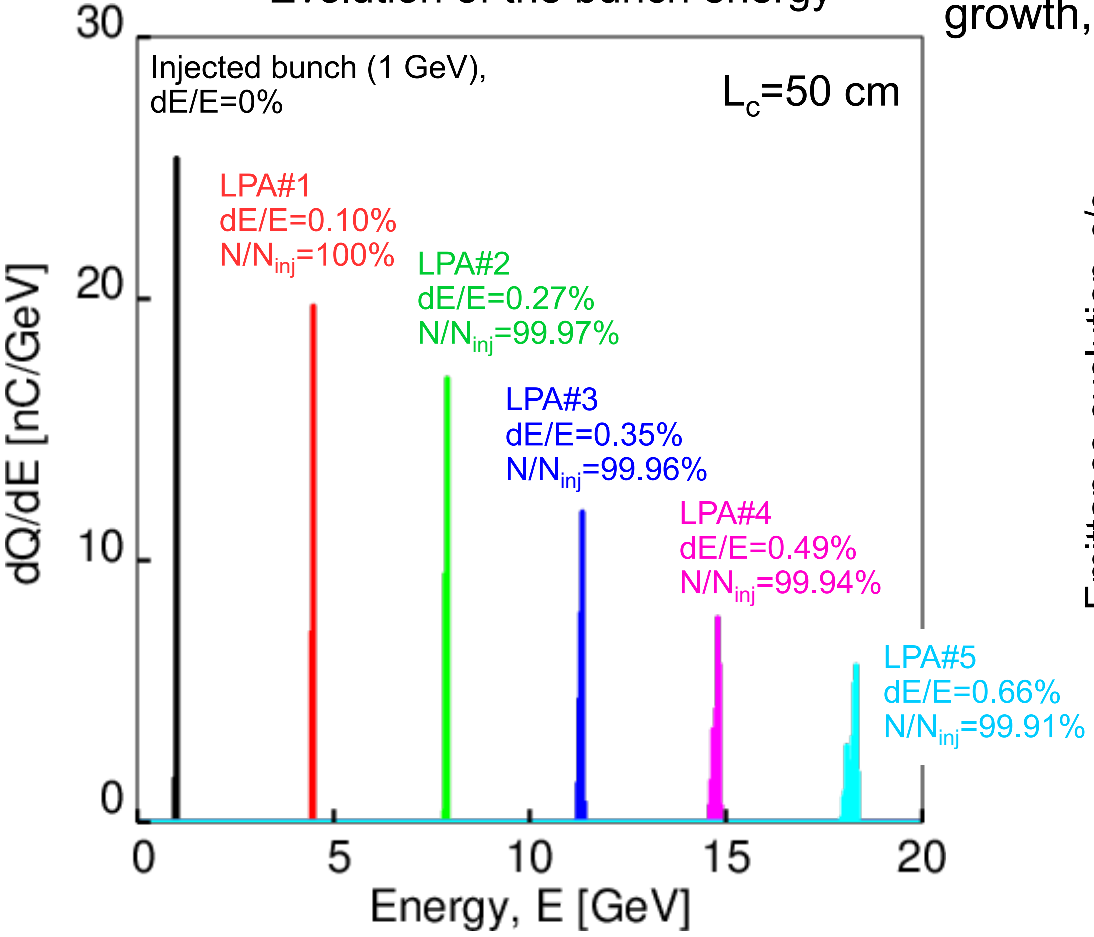


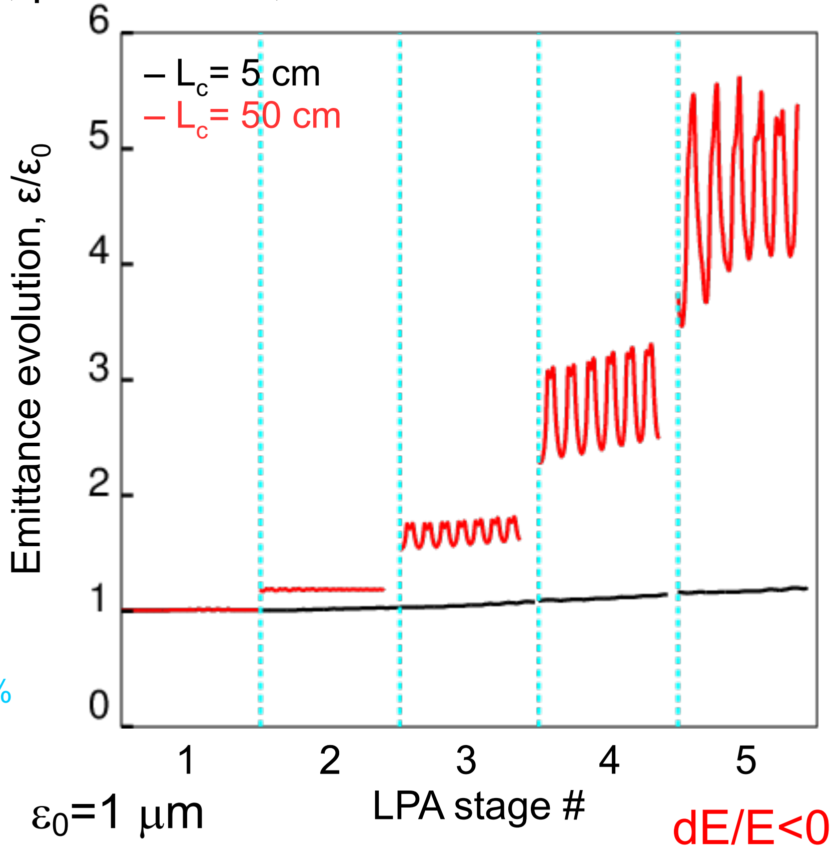
Emittance preservation requires development of achromatic inter-stage transport elements for e-beam.



Chromatic effects = particles with energy different from the “design” value are refocused at incorrect transverse location: mismatch, additional emittance growth, particle loss,…

Evolution of the bunch energy





ε_0=1 μm

Emittance growth from chromaticity in drifts:

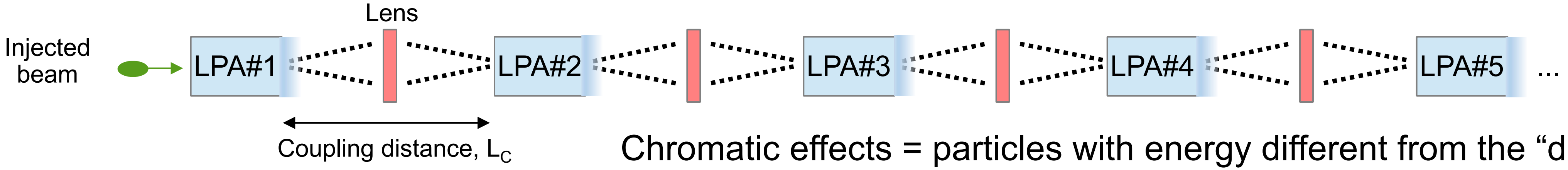
$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

P. Antici et al., JAP (2012)
M. Migliorati et al., PRAB (2013)

A.G.R Thomas and D. Seipt, PRAB (2022)

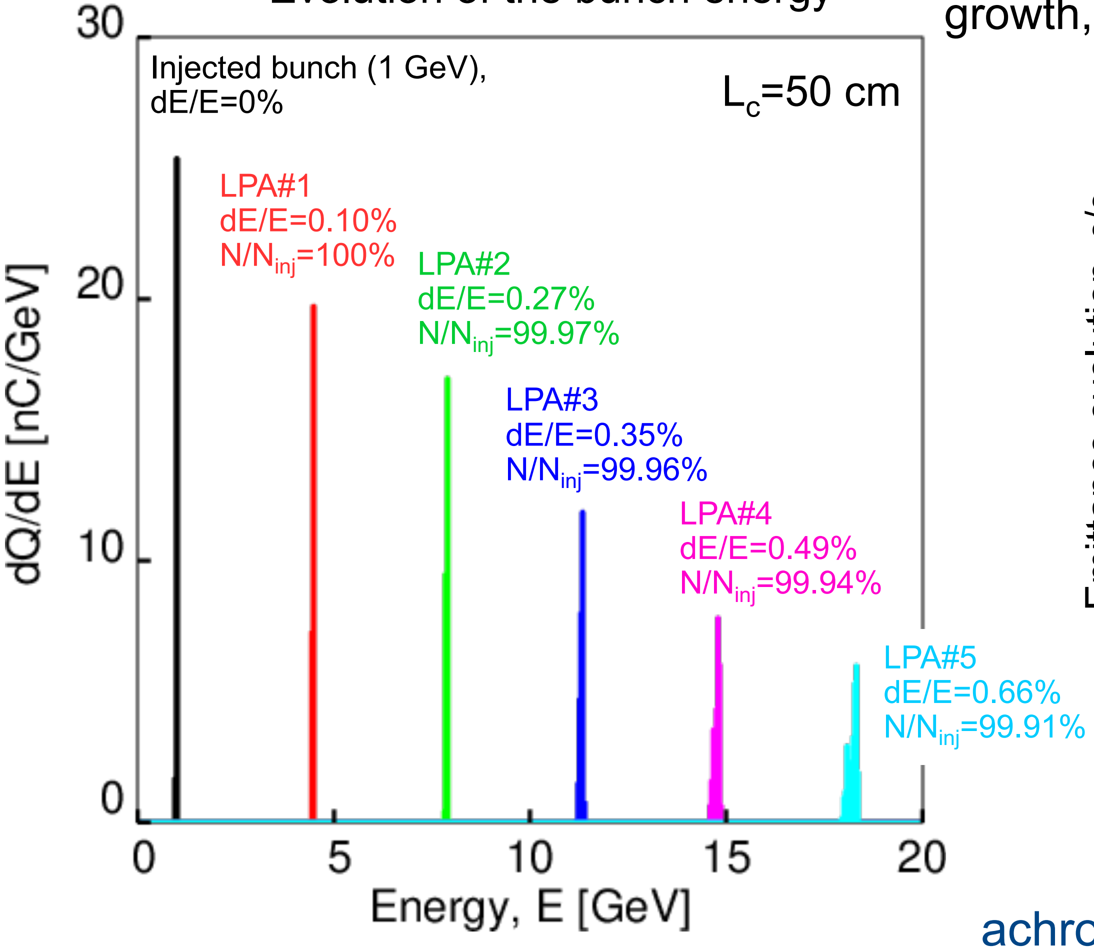
dE/E<0.001% required for emittance preservation in 85 stages (1 TeV)

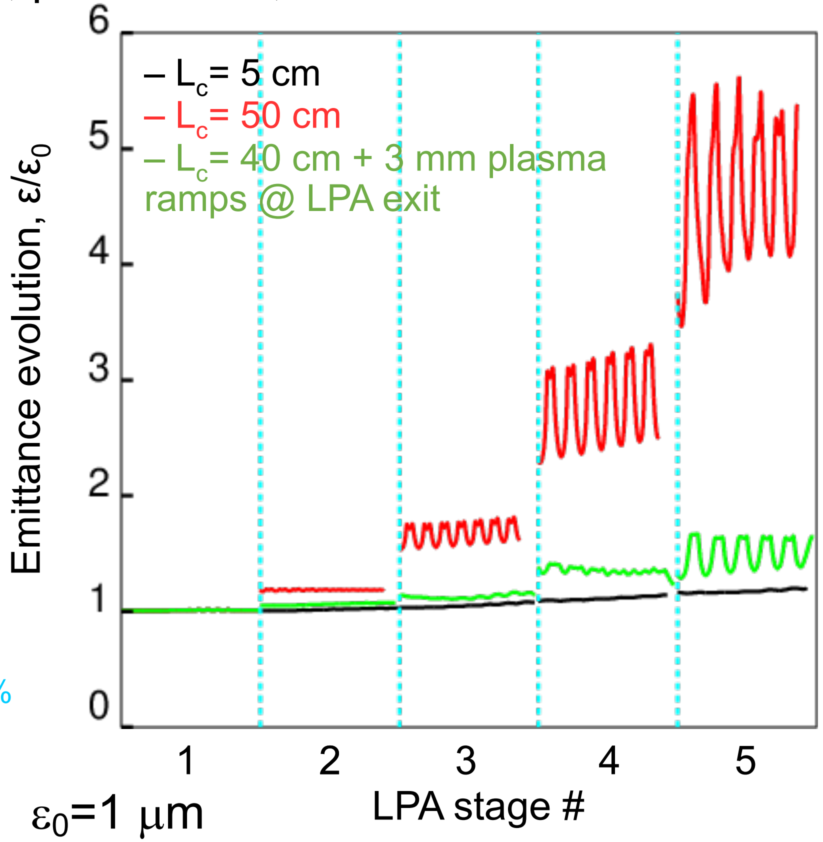
Emittance preservation requires development of achromatic inter-stage transport elements for e-beam.



Chromatic effects = particles with energy different from the “design” value are refocused at incorrect transverse location: mismatch, additional emittance growth, particle loss,…

Evolution of the bunch energy





ε_0=1 μm

Emittance growth from chromaticity in drifts:

$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\,\frac{s}{\gamma_0}$$

Exit ramp expands the beam: ε_0/σ_0 decreases!

P. Antici et al., JAP (2012)
M. Migliorati et al., PRAB (2013)

C. Lindstrøm, PRAB (2021)

→ Development of compact achromatic focusing optics (or with large chromatic acceptance) required

A channel-guided stage operating in the quasi-linear regime providing high-gradient, high-charge, and high-efficiency acceleration has been designed

Laser: U=8.9 J, λ_0=1.0 um, a_0=1.8, T_0=73 fs , w_0=41 μm
Plasma (hollow channel): n_0=0.96x10^{17} cm^{-3}, R_c=24 μm, stage length = 78 cm w/ optimal taper

Schroeder et al., NIMA (2016)

ΔW_{bunch}= 5.05 GeV (6.5 GV/m)
Q_{bunch}= 0.24 nC – L_{bunch}=30 μm – I_{bunch} =5 kA
Energy spread = 0.8%

Energy considerations:

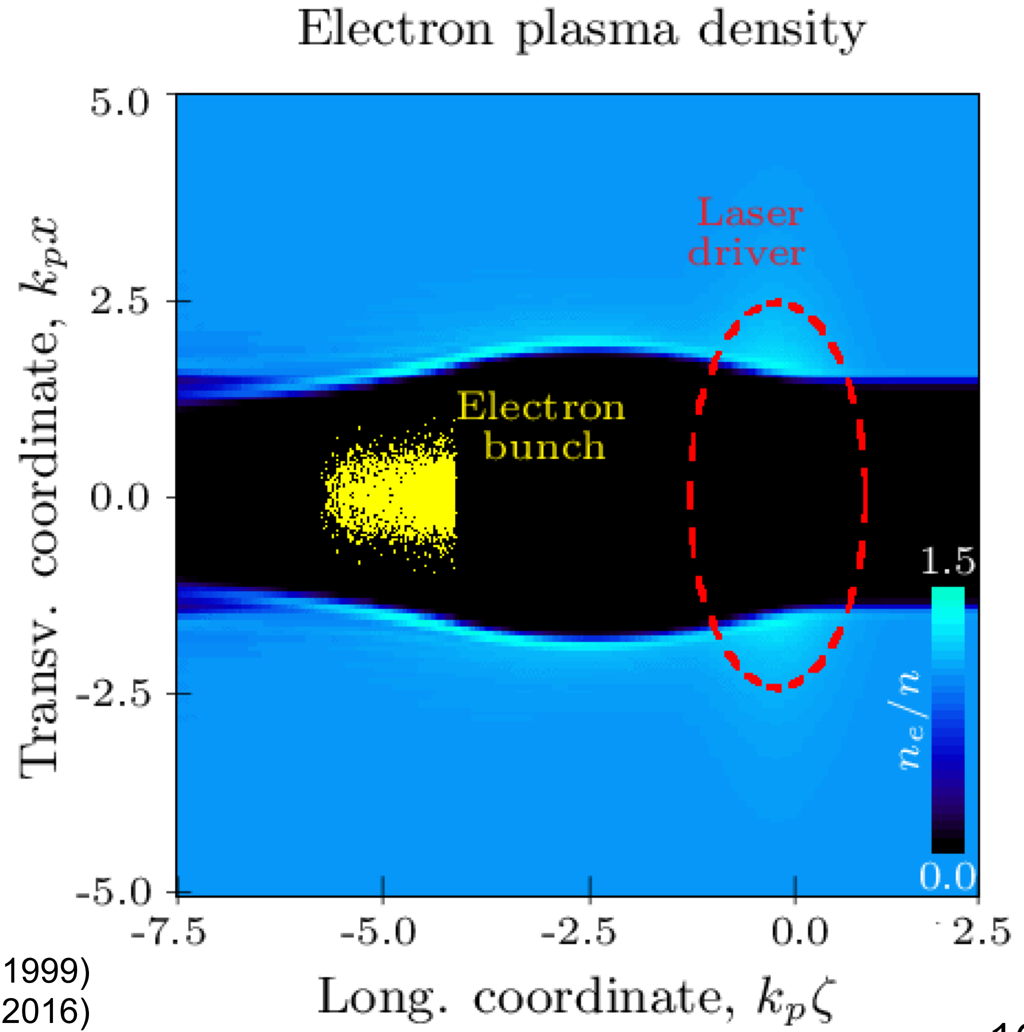
- Wake-to-bunch energy transfer = 68%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic

→ TeV-class linac → cascading a few 100s of LPA stages

→ Suitable for positron acceleration

→ Negligible emittance growth from Coulomb scattering and no energy spread from synchrotron radiation

→ Unstable w/o external focusing (mechanism for stabilization under investigation)



Schroeder et al., PRL (1999)
Gessner et al., Nat. Comm (2016)
Lindstrøm et al., PRL (2018)

Use of large bunch sizes (enabled by hollow channel) results in suppression of chromatic emittance growth during staging

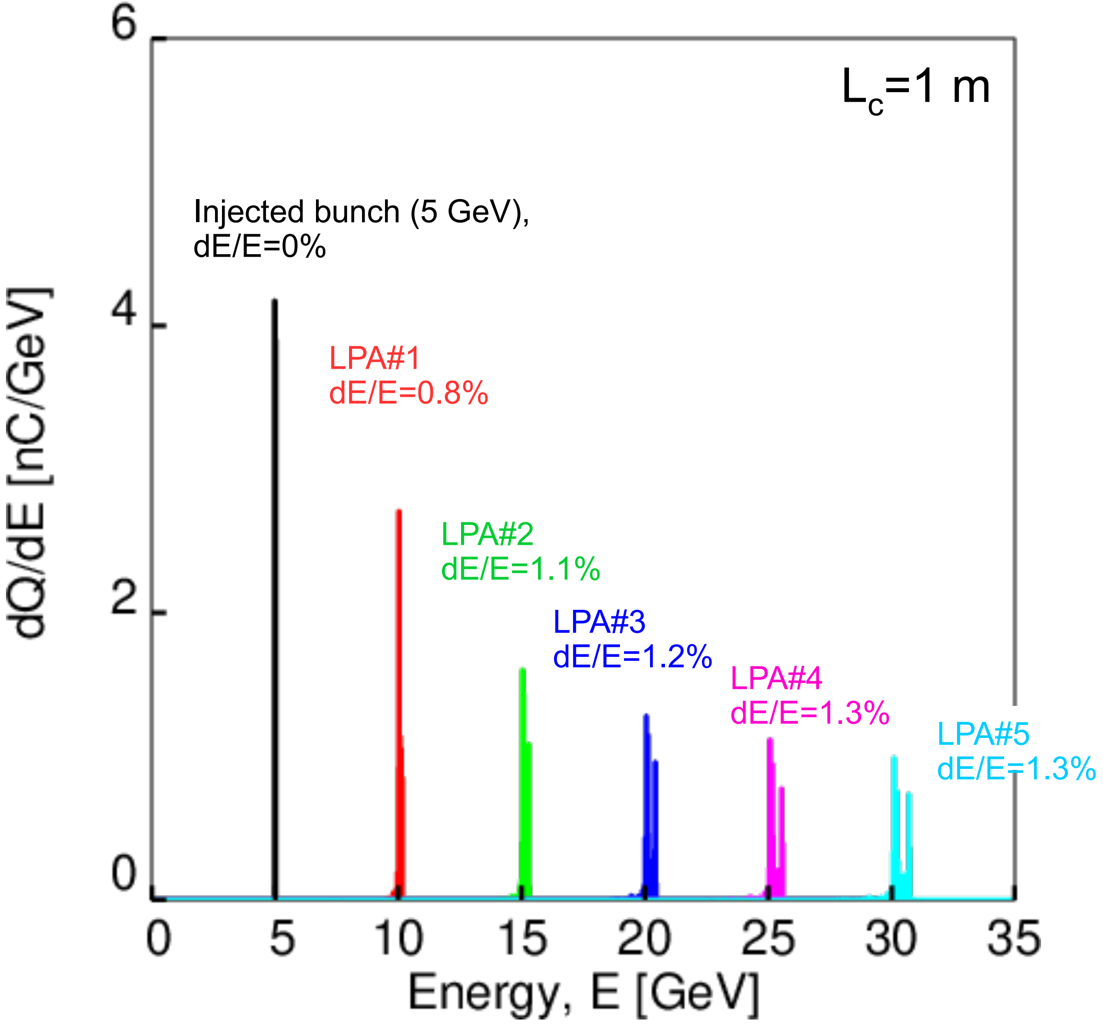
$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

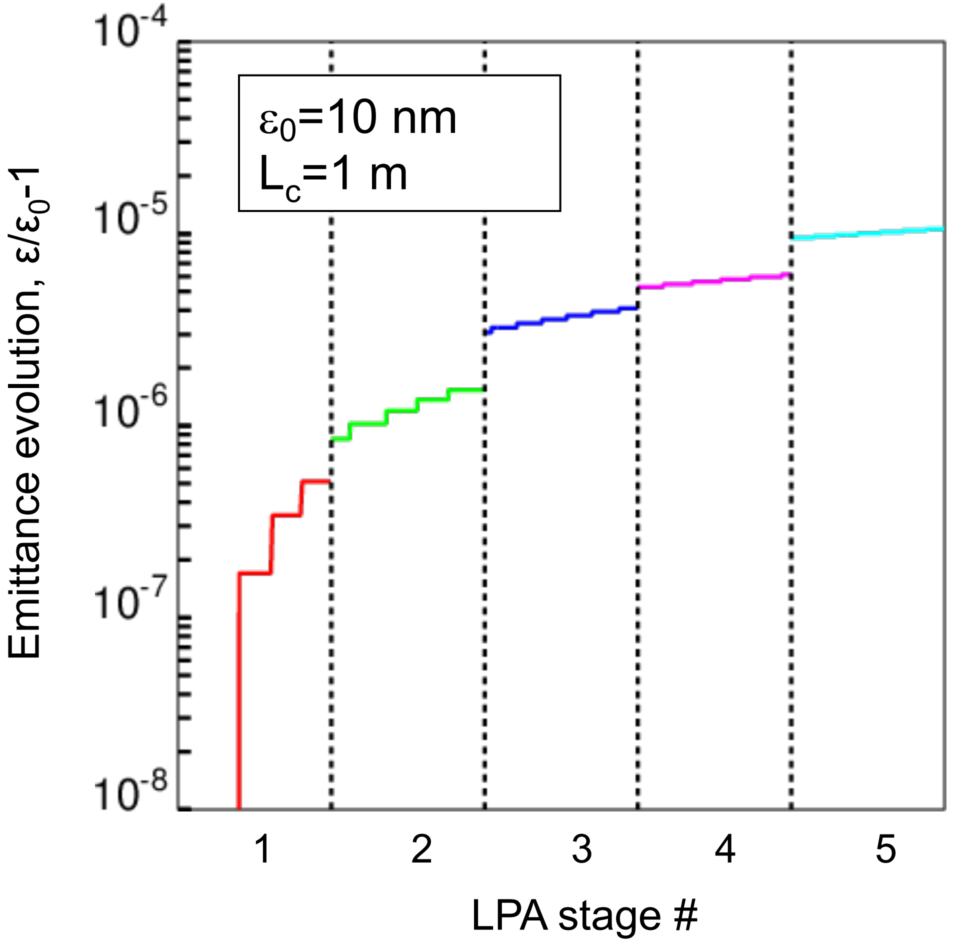
For multi-GeV bunches with ε_0= 10 nm, σ_0=5 μm, and ~1% energy spread:

→ $\Delta\varepsilon$ <<1 nm in meter-scale drifts

→ Applies to any stage where σ_0 can be controlled

Evolution of the bunch energy





Summary

- Characteristics of **channel-guided** and **self-guided** LPAs driven by a laser with given (fixed) energy have been discussed:
    - Energy gain in channel-guided LPAs is larger than is self-guided LPAs;
    - Optimal charge in self-guided LPAs (i.e., operating in the nonlinear/bubble regime) is larger than that in channel-guided LPAs;
    - Technique to reduce final energy spread based on wake overloading has been discussed;

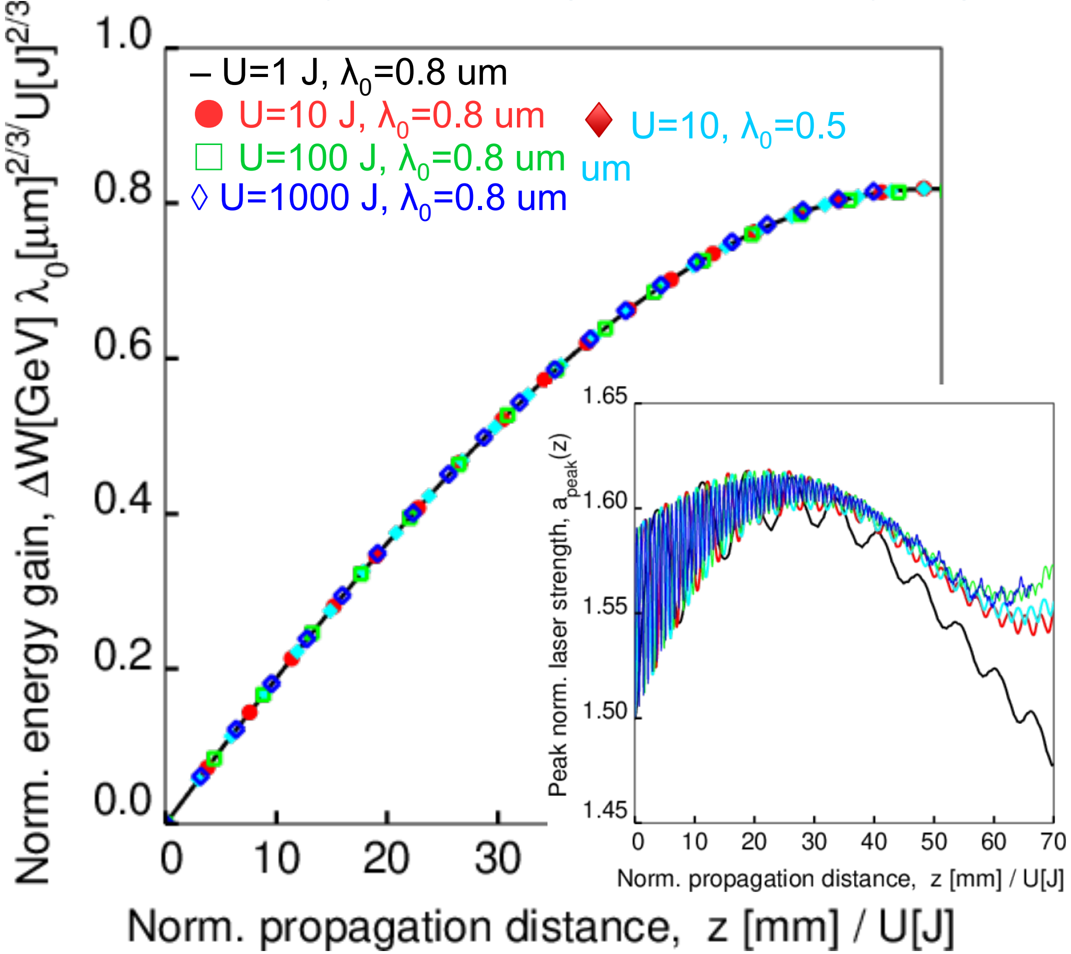
w/ scaling laws can be used to design and analyze collider-relevant LPA stages

- A **self-guided LPA** stage operating in the bubble regime providing high-gradient, high-charge, high-efficiency, and quality-preserving acceleration for collider applications has been presented → Preservation of emittance during staging requires use of tailored plasma ramps at the exit of LPA stages + development of compact achromatic focusing optics.
- A **channel-guided (hollow channel) LPA** stage operating in the quasi-linear regime providing high-gradient and high-efficiency acceleration has been presented → Large bunch size enabled by hollow channel results in suppression of chromatic emittance growth during focusing. Stabilization must be addressed.

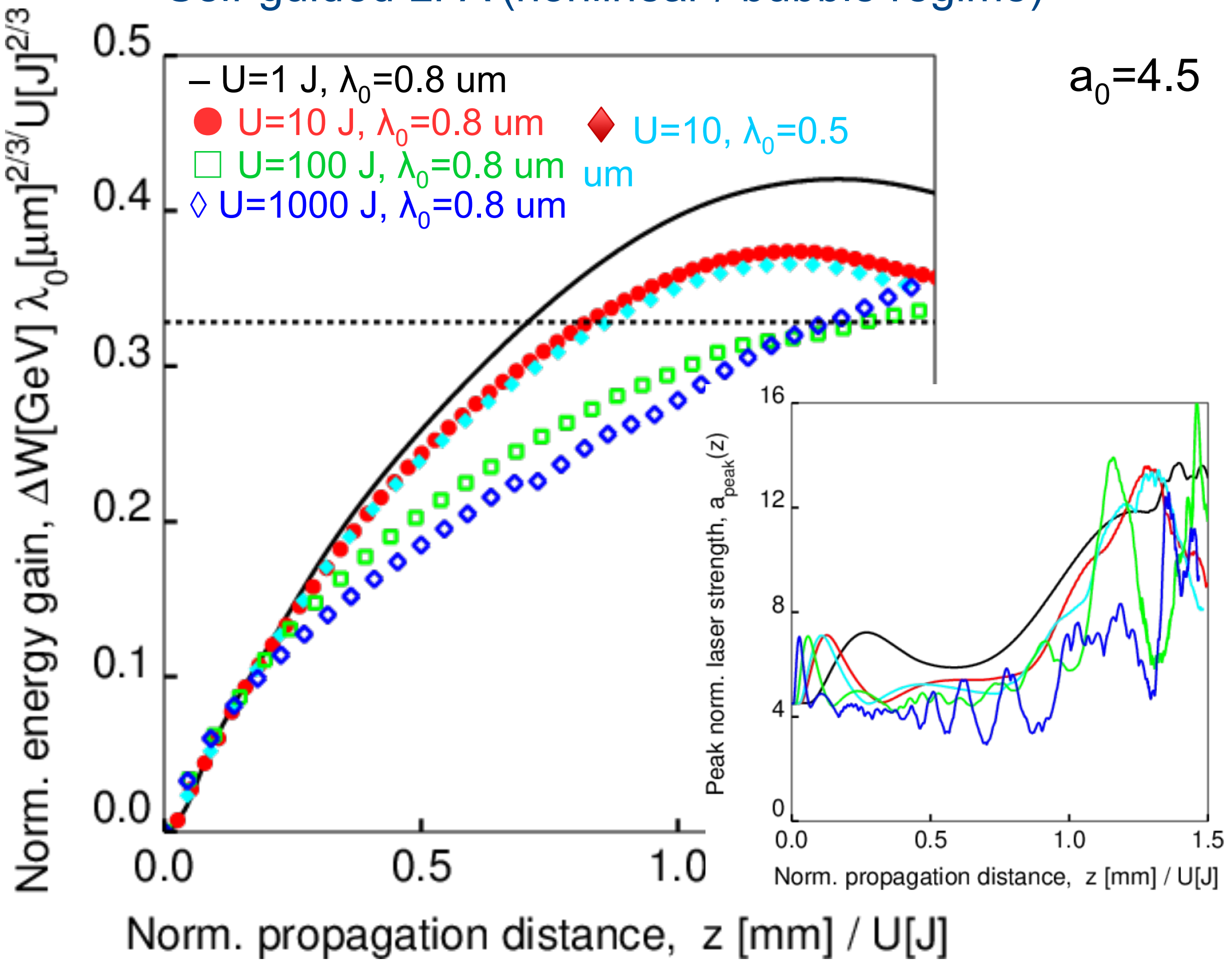
LPA characteristics for different values of laser energy and wavelength can be obtained with scaling laws (for fixed normalized laser parameters)

Channel-guided LPA (quasi-linear regime)

a_0=1.5
k_pL=0.6
k_0w=3



Self-guided LPA (nonlinear / bubble regime)



a_0=4.5

Scaling laws → Energy gain: $\Delta W_{bunch} \sim U^{2/3}\ \lambda_0^{-2/3}$ – Stage length: $L_{acc} \sim U$

→ Scaling laws approximately satisfied for self-guided regimes owing to imperfect guiding of the laser