Physics considerations for laser-plasma linear colliders

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P5 report recommmends effort towards development of 10 TeV pCM collider and encourages development of self-consistent design for a wakefield-based collider.

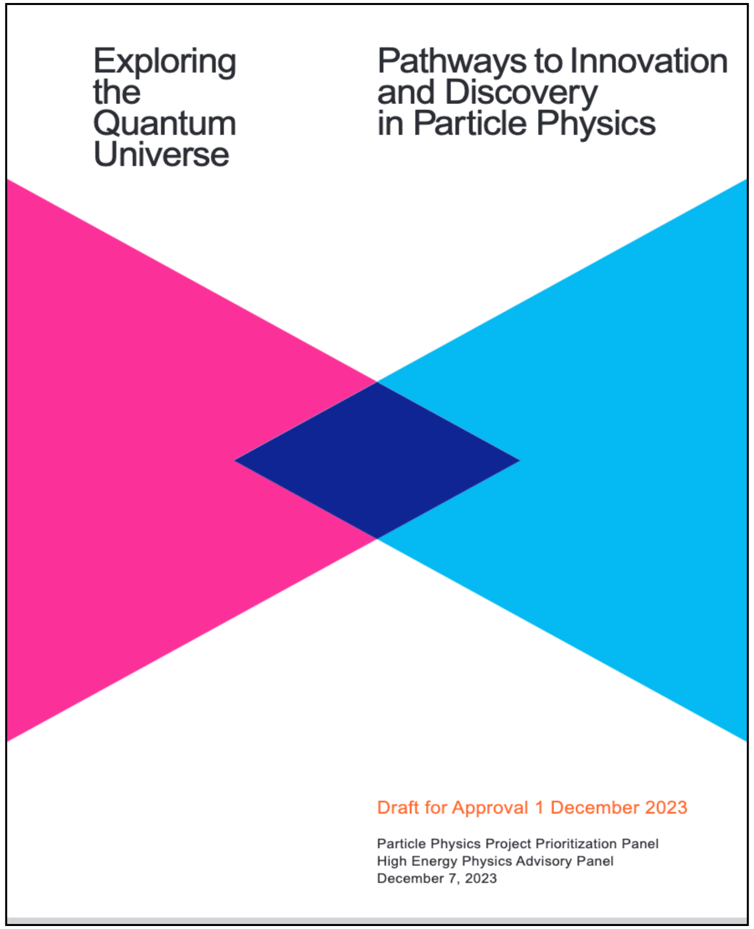
“Recommendation 4: **Support** a comprehensive **effort** to develop the resources - theoretical, computational, and technological — essential to our 20-year vision for the field. This includes an **aggressive R&D program** that, while technologically challenging, could yield revolutionary accelerator designs that **chart a realistic path to a 10 TeV pCM collider**.”

“Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider**, such as a muon collider, a proton collider, or **possibly** an electron-positron collider **based on wakefield** technology.”

→ Challenges with all technologies…

“**Wakefield** concepts for a collider are in the early stages of development. **A critical next step is the delivery of an end-to-end design concept**, including cost scales, **with self-consistent parameters** throughout.”

`https://www.usparticlephysics.org/2023-p5-report/`



Exploring
the
Quantum
Universe

Pathways to Innovation
and Discovery
in Particle Physics

Draft for Approval 1 December 2023

Particle Physics Project Prioritization Panel
High Energy Physics Advisory Panel
December 7, 2023

Overview of the presentation

- **Schematic for a multi-TeV-class LPA-based collider**
  → Use “straw-person” design to identify key R&D challenges (linac only in this talk);

- **Characterize LPA performance for fixed laser energy and wavelength (i.e., fixed laser technology)**
  → Max. energy gain, stage length, optimal bunch charge, etc. in different regimes (e.g., self-guided, channel-guided);

- **Present examples of collider-relevant stages (self-guided and channel-guided)**
  → Discuss beam quality preservation during staging;

- **Recap of challenges & potential solutions**

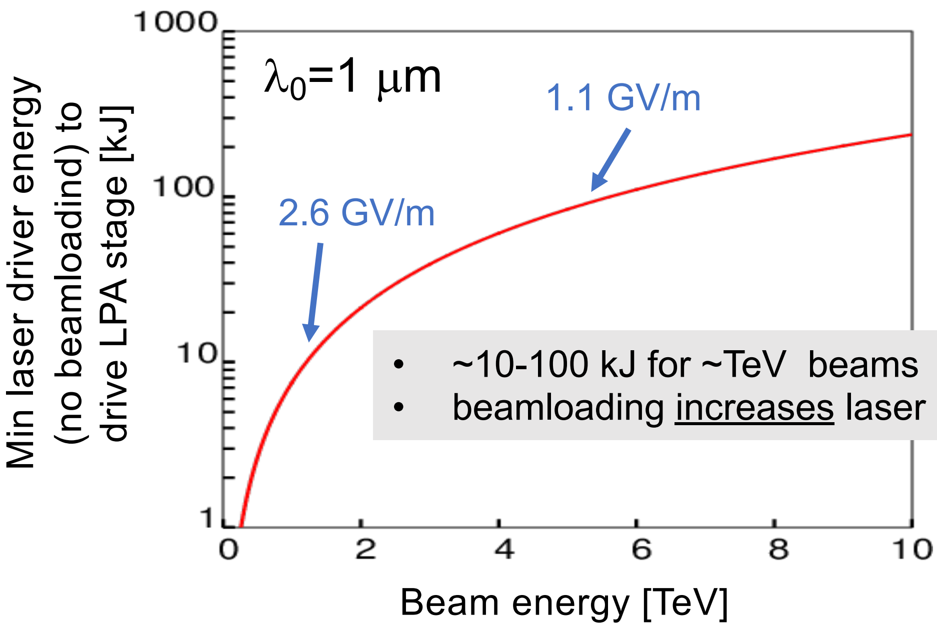
- **Summary and conclusions**

Conceptual design of a multi-TeV-class LPA-based collider: preliminary considerations

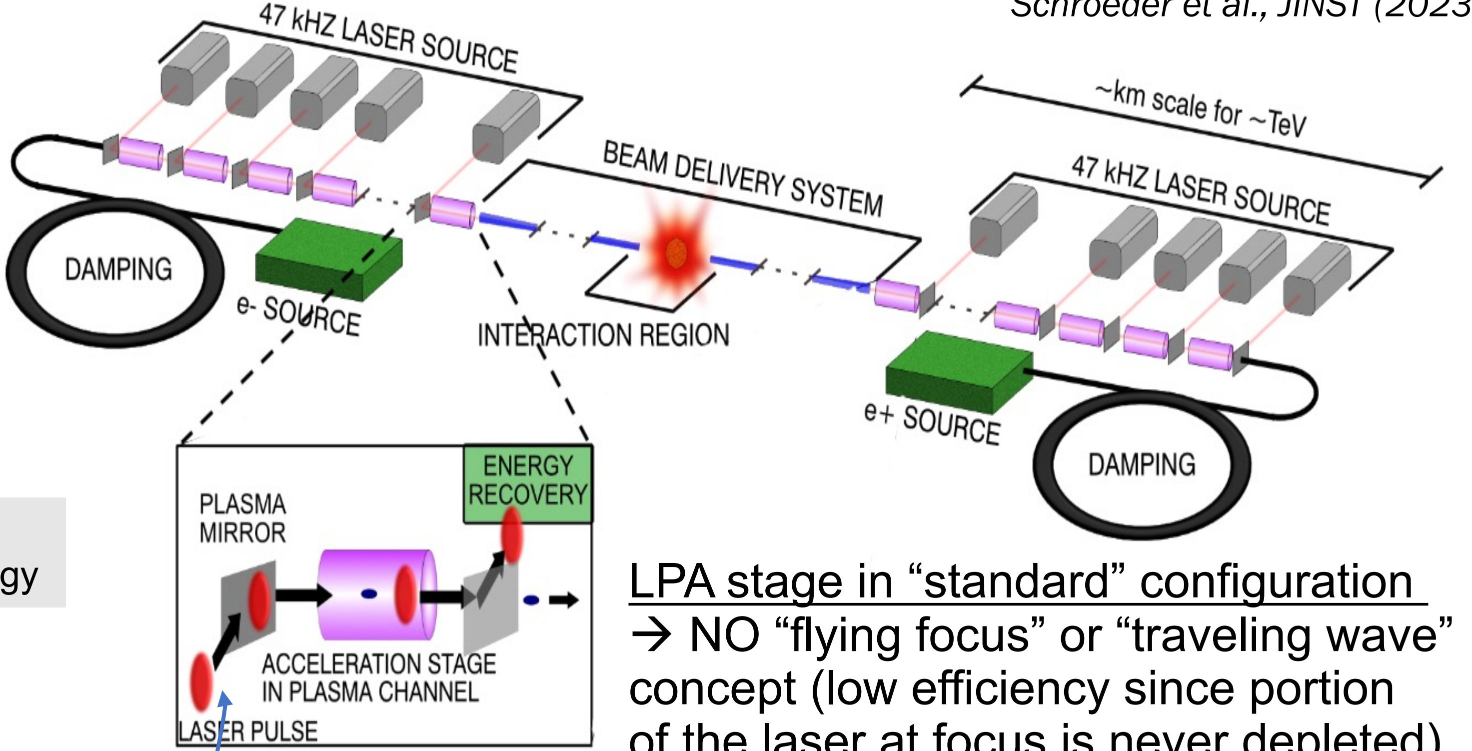
Setup based on staging of LPAs (high av. gradient → length <1 km/TeV)

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

Staging → path to high-energy maintaining low laser energy (and high gradient)



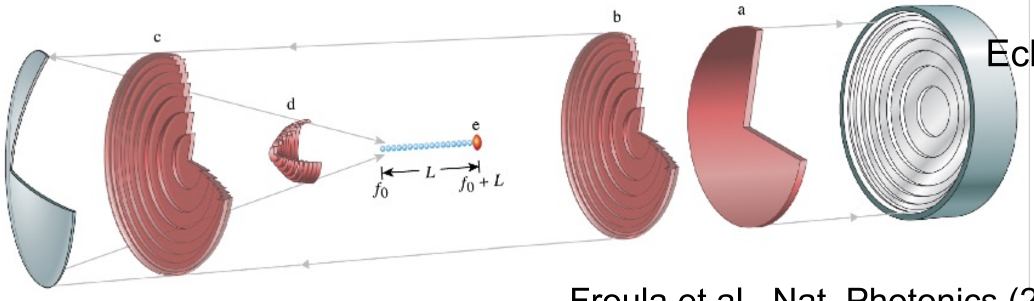
- ~10-100 kJ for ~TeV beams
- beamloading increases laser energy



LPA stage in "standard" configuration
→ NO "flying focus" or "traveling wave" concept (low efficiency since portion of the laser at focus is never depleted)

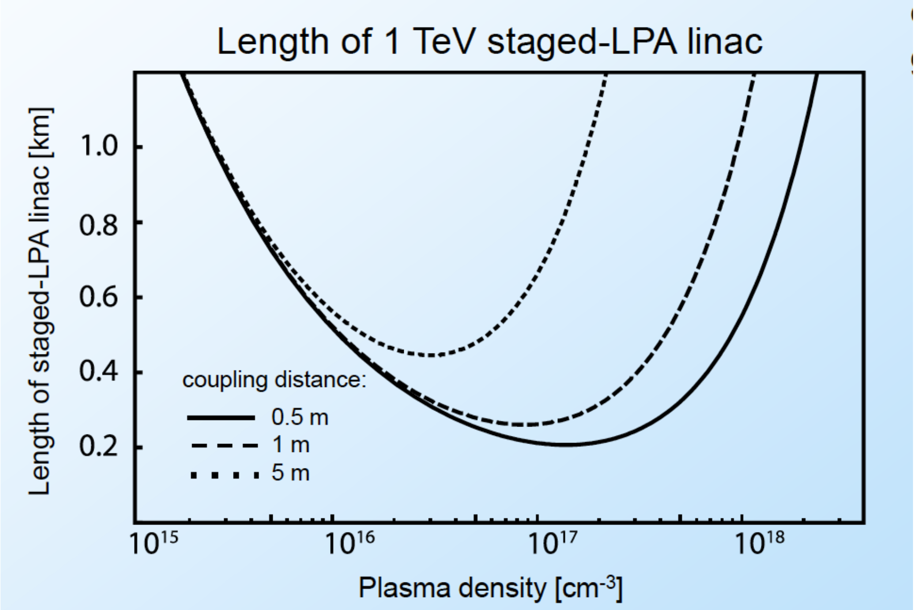
- Staging requires in-coupling new laser pulse at each stage
- Keeping high averag[illegible] [illegible]es short in-couplin[illegible] **[illegible]ma mirrors** (L_c<~ 1 m)

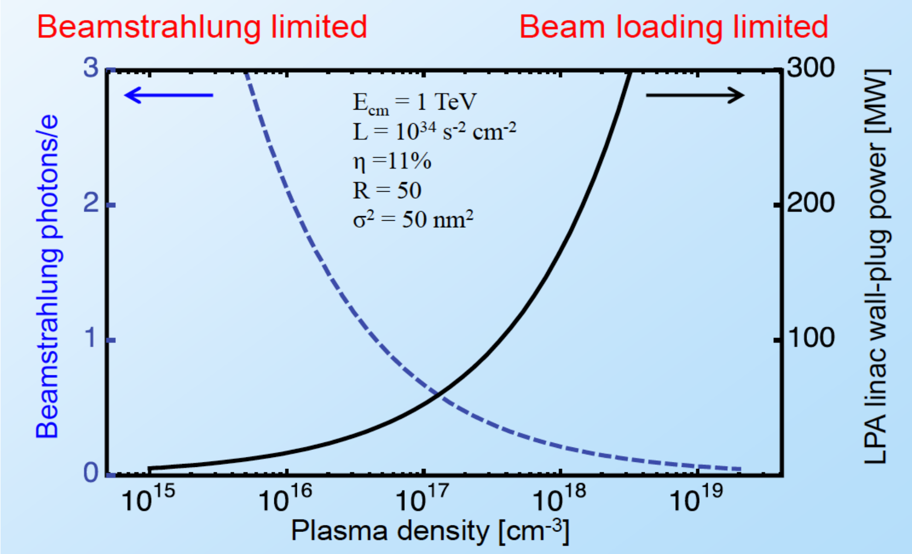
See talk by M. Backhouse (Wed 12pm)



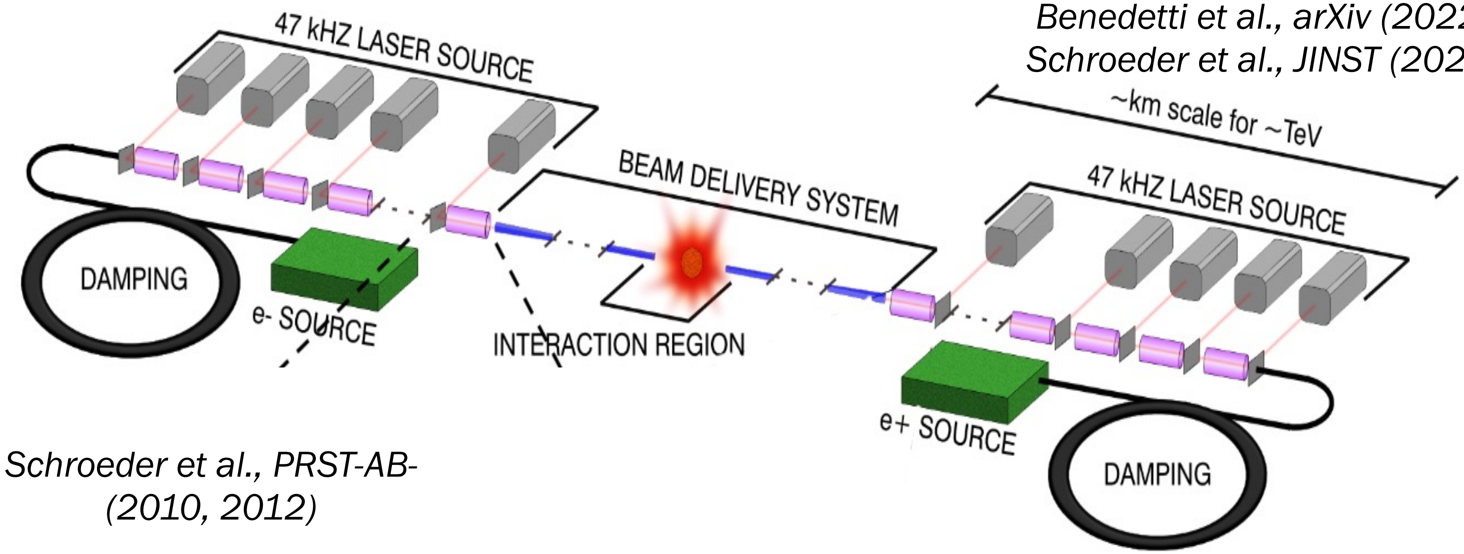
Froula et al., Nat. Photonics (2018)
Palastro et al., PRL (2020)

Conceptual design of a multi-TeV-class LPA-based collider: LPA and bunch properties





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



Schroeder et al., PRST-AB- (2010, 2012)

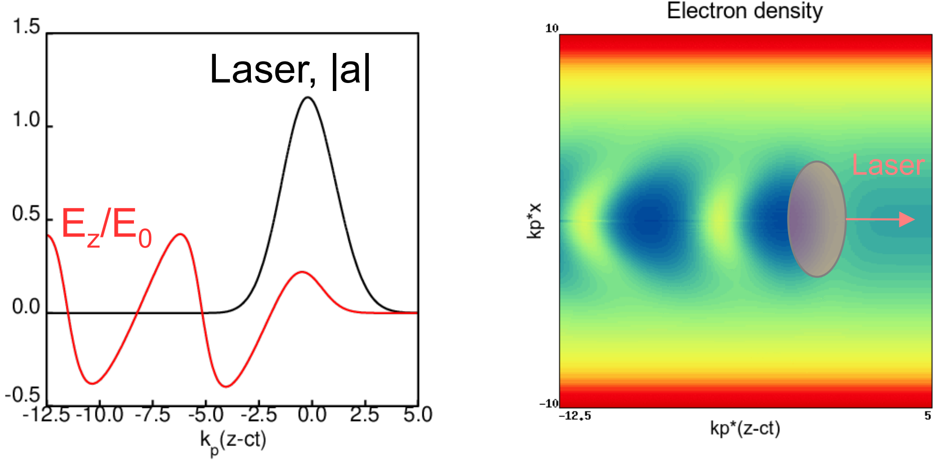
LPA properties determined by minimization of wall-plug power, beamstrahlung, and linac length + achieve desired luminosity (~10^{34} cm^{-2} s^{-1} @ 1 TeV):

- 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, …)
- ~100s LPA stages/TeV

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

Characterization of LPA performance in different regimes for given laser technology (i.e., fixed energy and wavelength)

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** ($P/P_c \sim 1$)

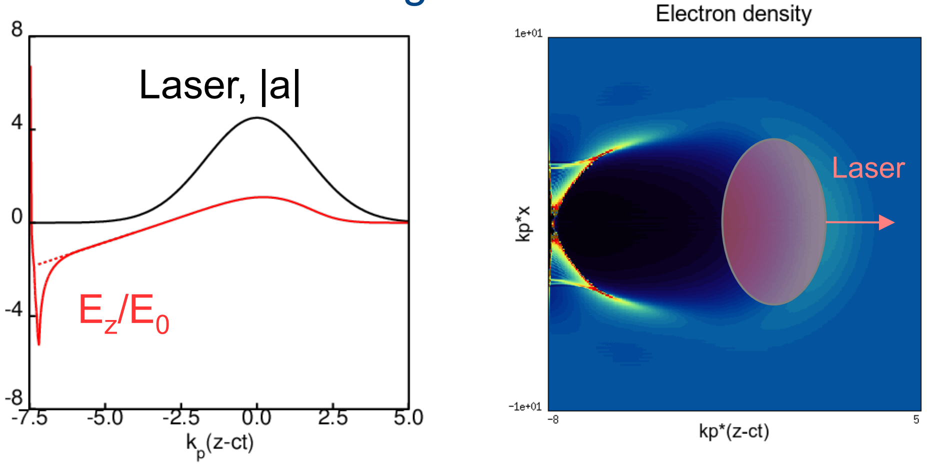
→ Operates best in quasi-linear regime ($a_0 <\sim 3$), nonlinear possible

→ 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: $\Delta W_{\mathrm{bunch}} \sim n_0^{-1} \lambda_0^{-2}$

→ 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)

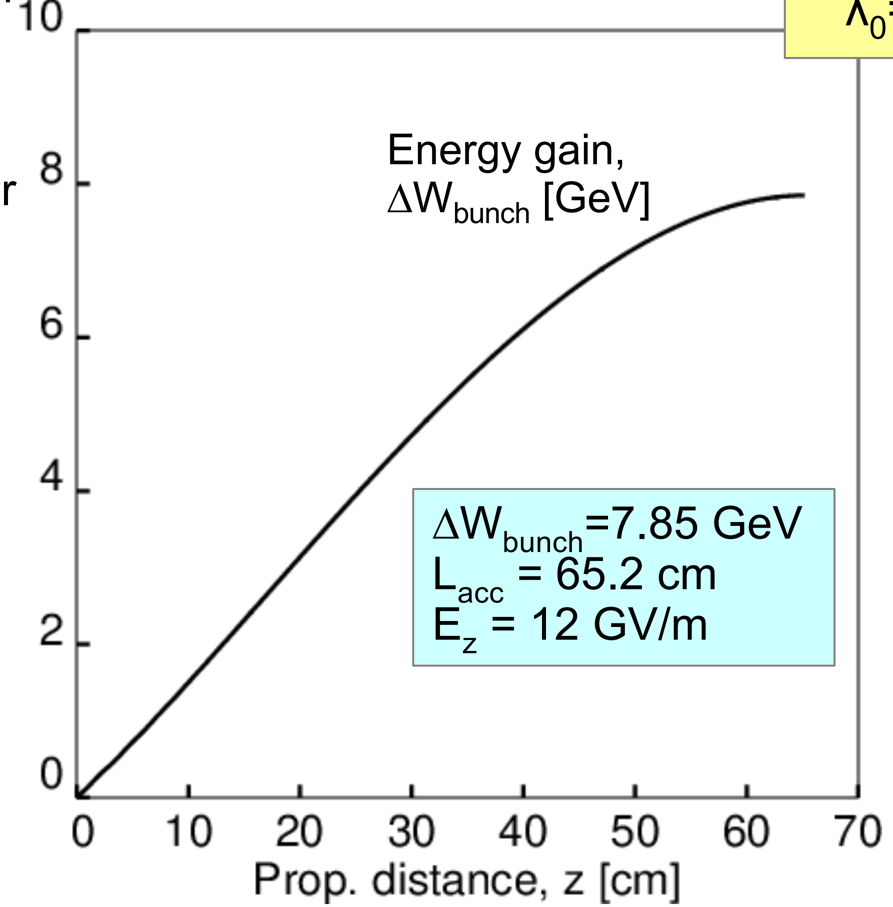
For given laser energy and wavelength max energy gain in channel-guided LPAs is larger than in self-guided LPAs (for negligible beamloading and short bunches)

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

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

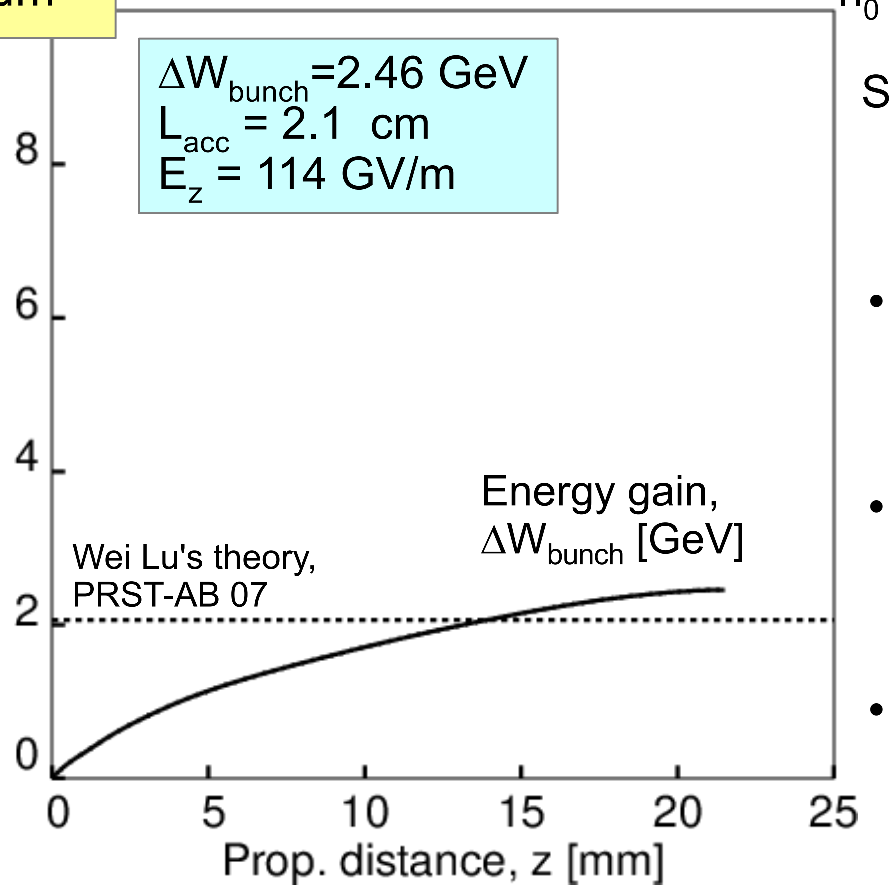


ΔW_{bunch}=7.85 GeV
L_{acc} = 65.2 cm
E_z = 12 GV/m

Self-guided LPA (nonlinear / bubble regime)

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

- 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



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

→ 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

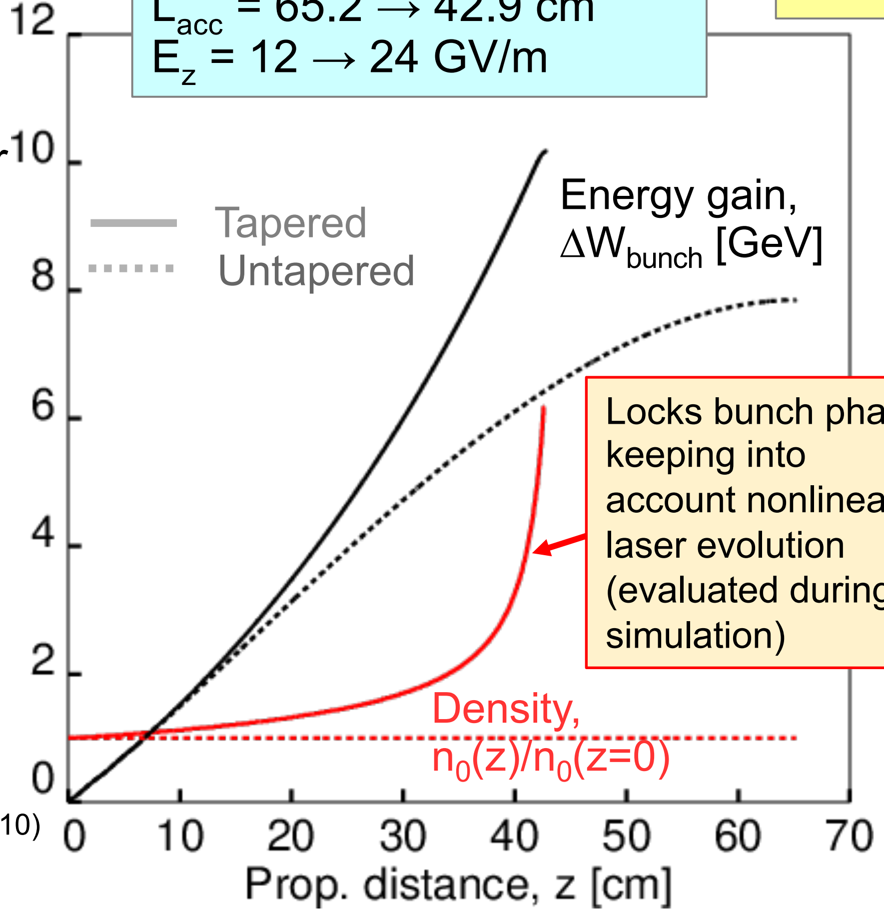
Energy gain in quasi-linear channel-guided stages can be increased with optimal (includes laser evolution effects) longitudinal density tapering

Laser driver:
U=10 J,
λ_0=0.8 μm

Channel-guided LPA (quasi-linear regime)

n_0=1.05x10^{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



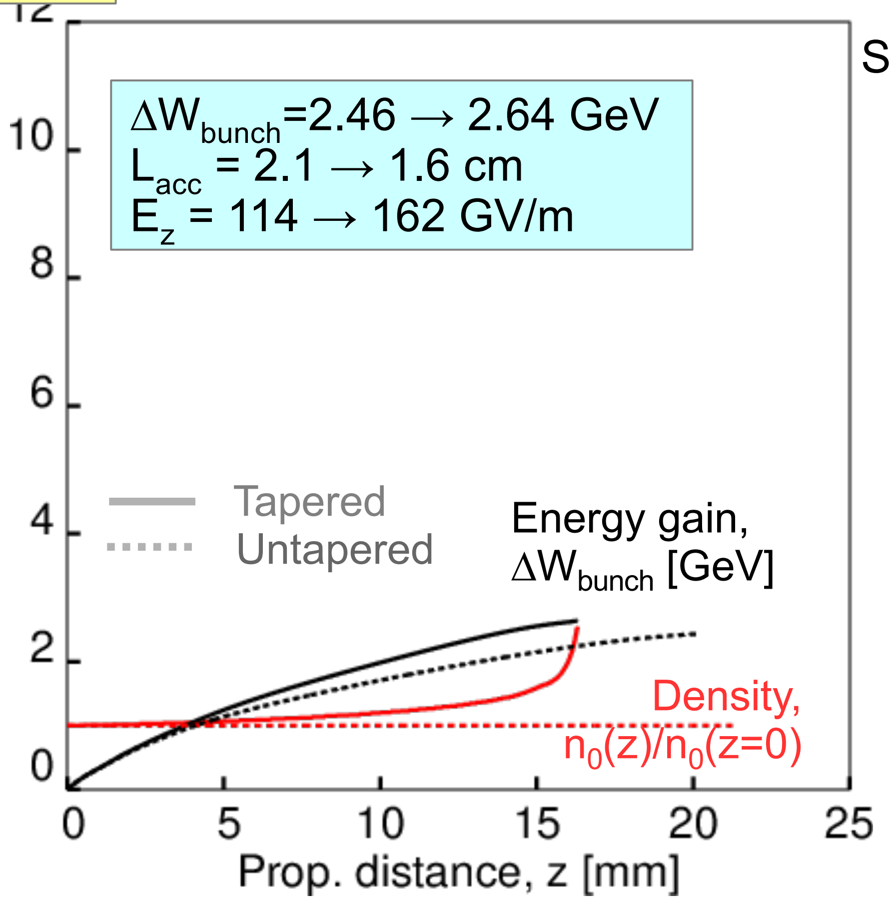
Locks bunch phase keeping into account nonlinear laser evolution (evaluated during simulation)

A. Pukhov, PRE (2008)
W. Rittershofer, POP (2010)

Self-guided LPA (nonlinear / bubble regime)

n_0=1.14x10^{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

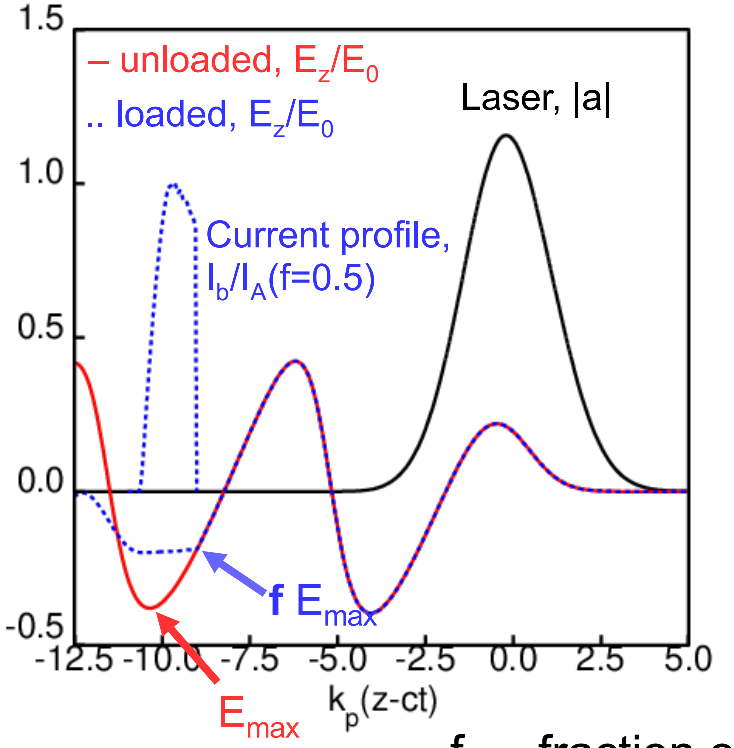


→ Energy gain in channel-guided LPAs can be ~4 times larger than in self-guided LPAs w/ tapering
→ Density tapering more effective for channel-guided/quasi-linear stages than for self-guided/nonlinear stages

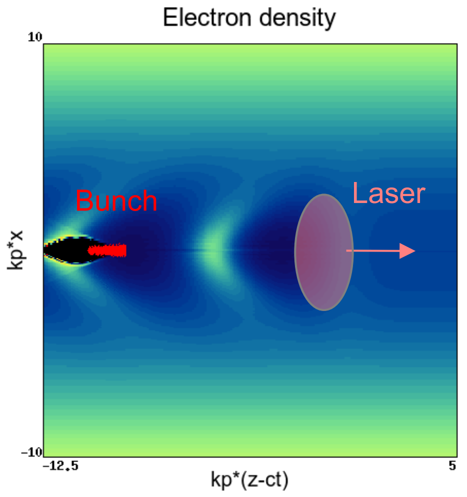
Determining characteristic charge that can be accelerated in an LPA requires identifying bunch profile that flattens the wake (i.e., absorbs energy from the wake)

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

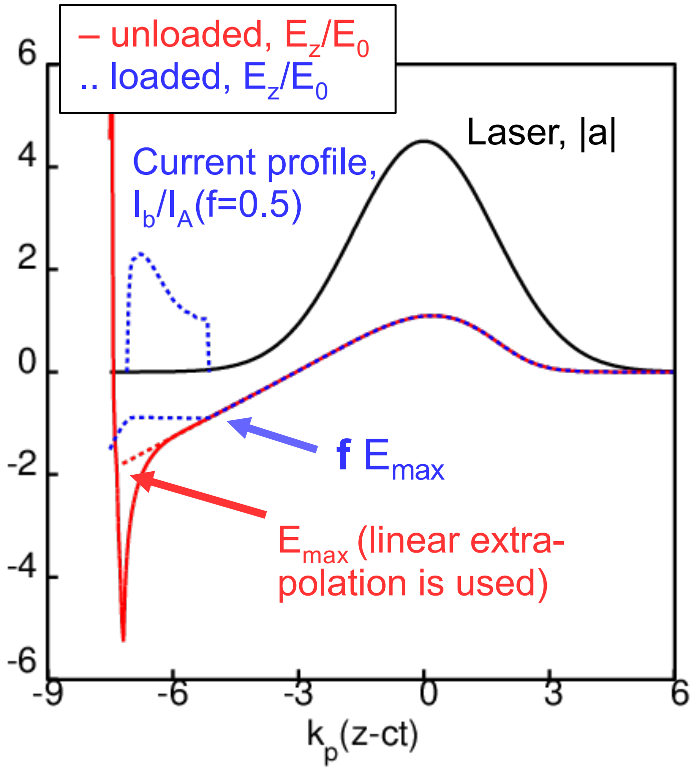
Channel-guided LPA (quasi-linear regime)



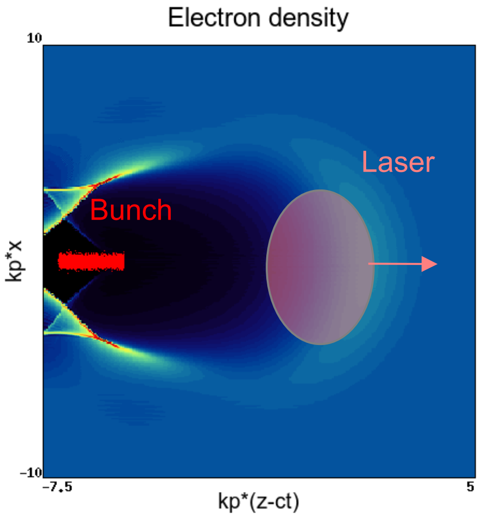
$a_0=1$, $k_pw_0=4$, $k_pL=1.8$



Self-guided (nonlinear / bubble regime)



$a_0=4.5$



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

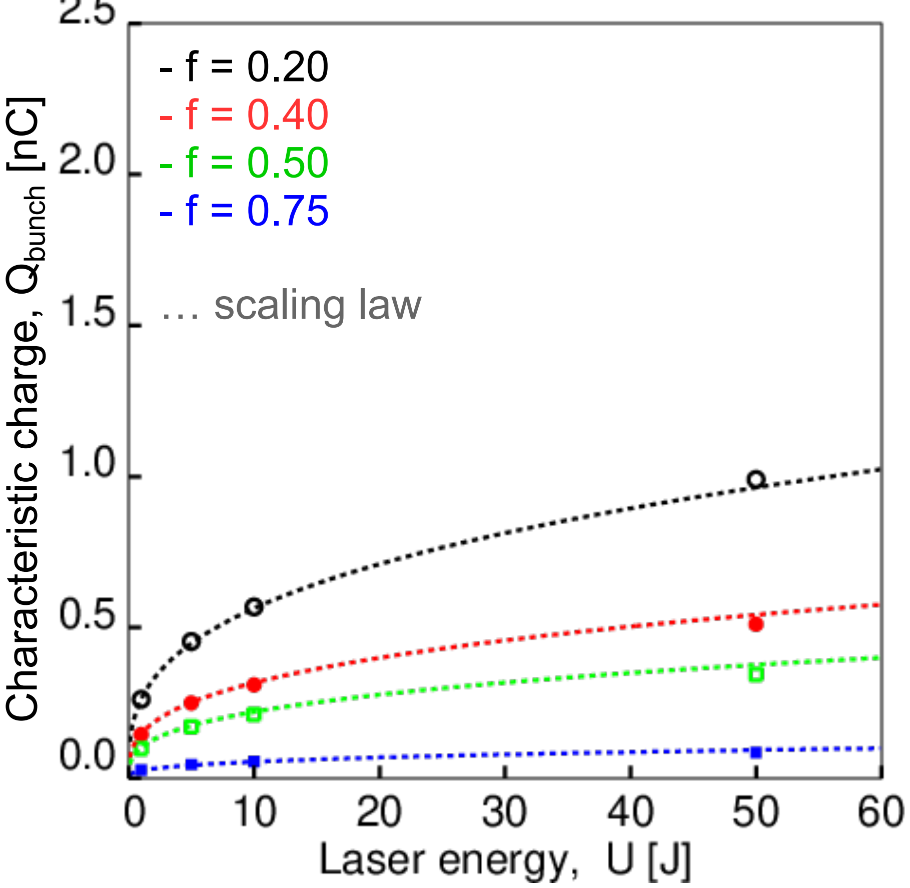
- Linear regime (i.e., $E_z/E_0 << 1$) → triangular profile (Katsouleas et al., Part. Accel., 1987)
- Blowout regime (requires $\delta n \sim n_0$, i.e., $a_0 > 8\text{-}10$) → trapezoidal profile (Tzoufras et al., PRL, 2009)

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

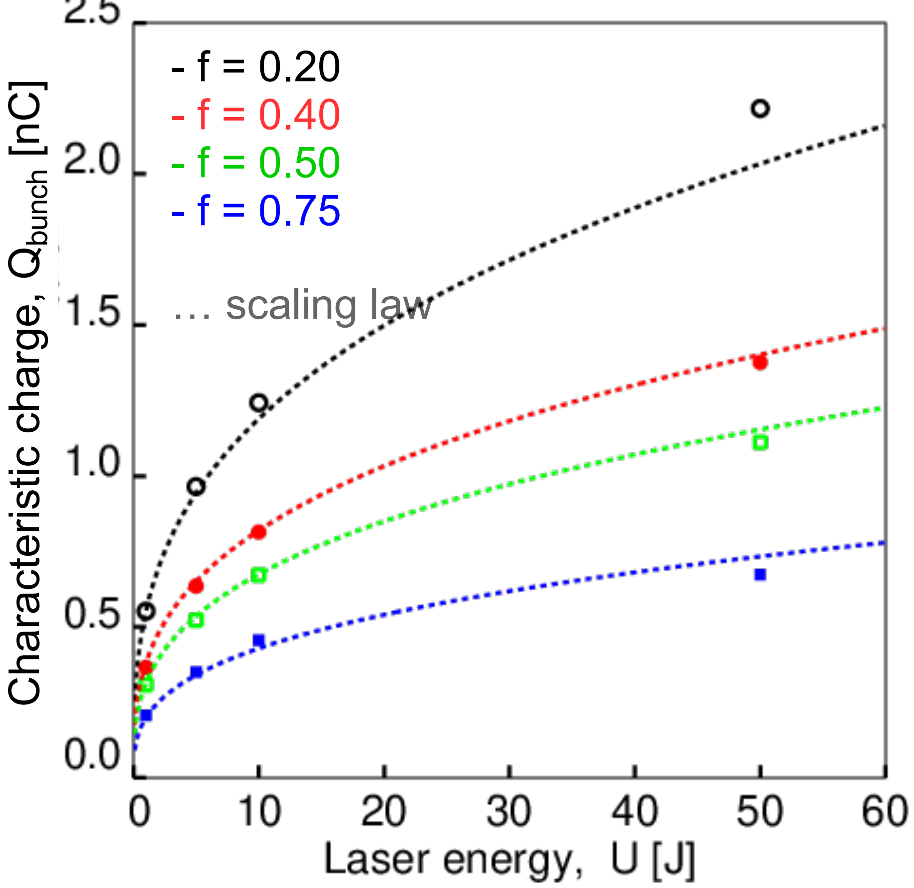
For given laser energy the characteristic bunch charge accelerated in self-guided LPAs is larger than in channel-guided LPAs

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

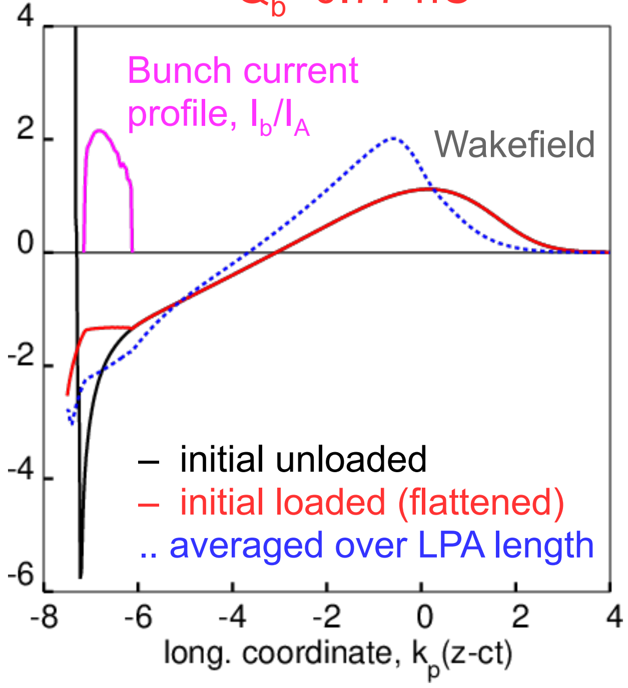
Scaling of the accelerated charge: $Q_{bunch}(U, \lambda_0) \sim U^{1/3} \lambda_0^{2/3}$

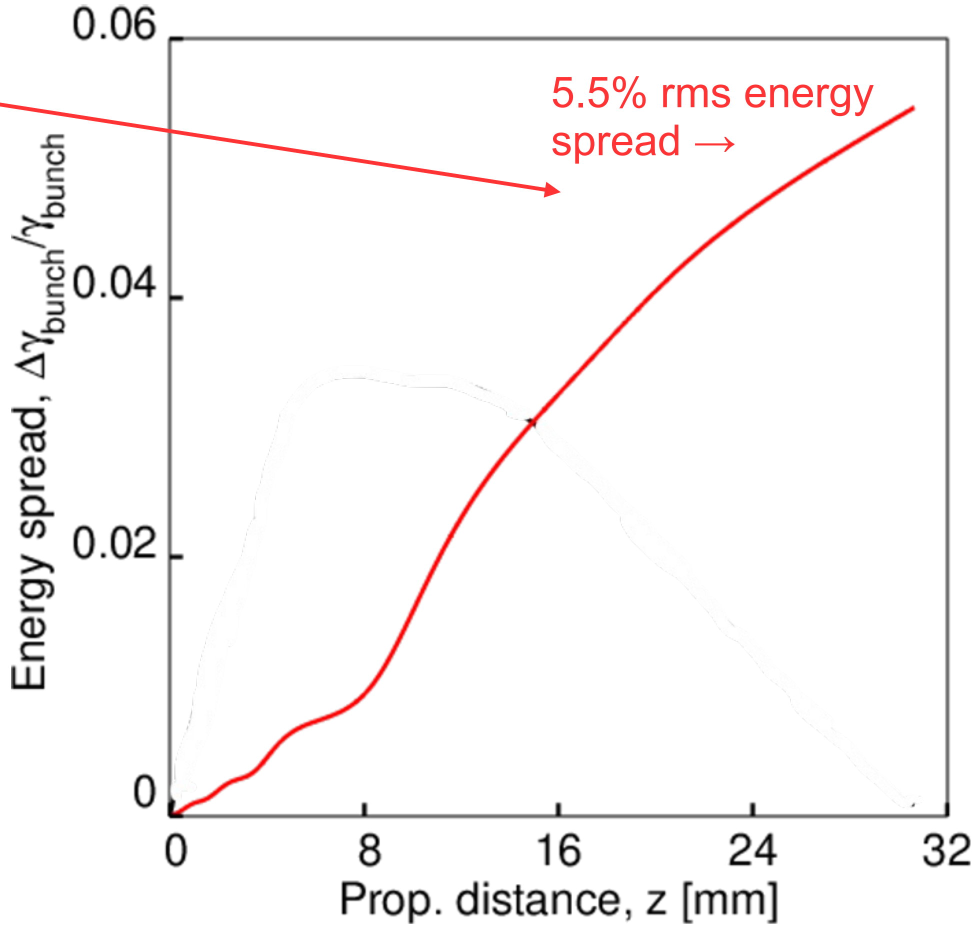
→ Charge in self-guided LPAs is >2-8 times larger than for channel-guided LPAs (owing to larger acc. gradient)

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

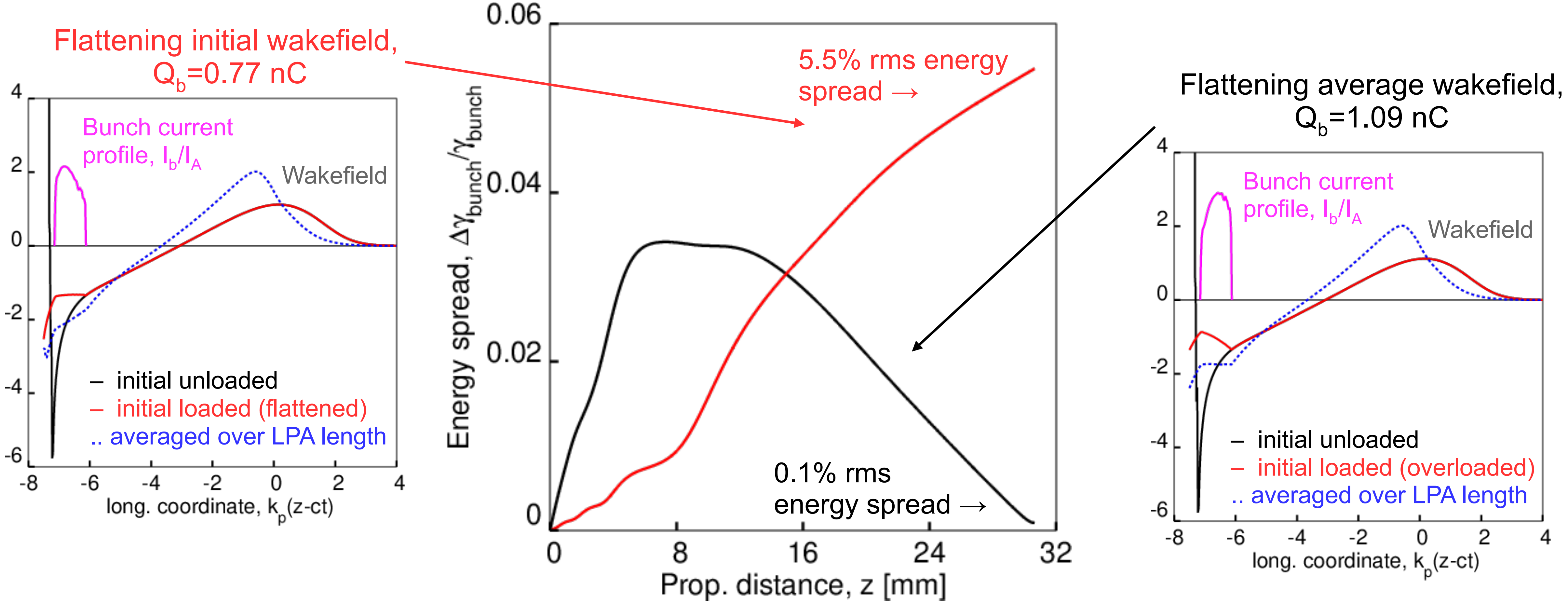




- Current profile that flattens initial wake not optimal to minimize energy spread
  → bunch acquires energy chirp (= energy spread) because of laser evolution

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

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 →

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

→ ~320 LPA stages/TeV

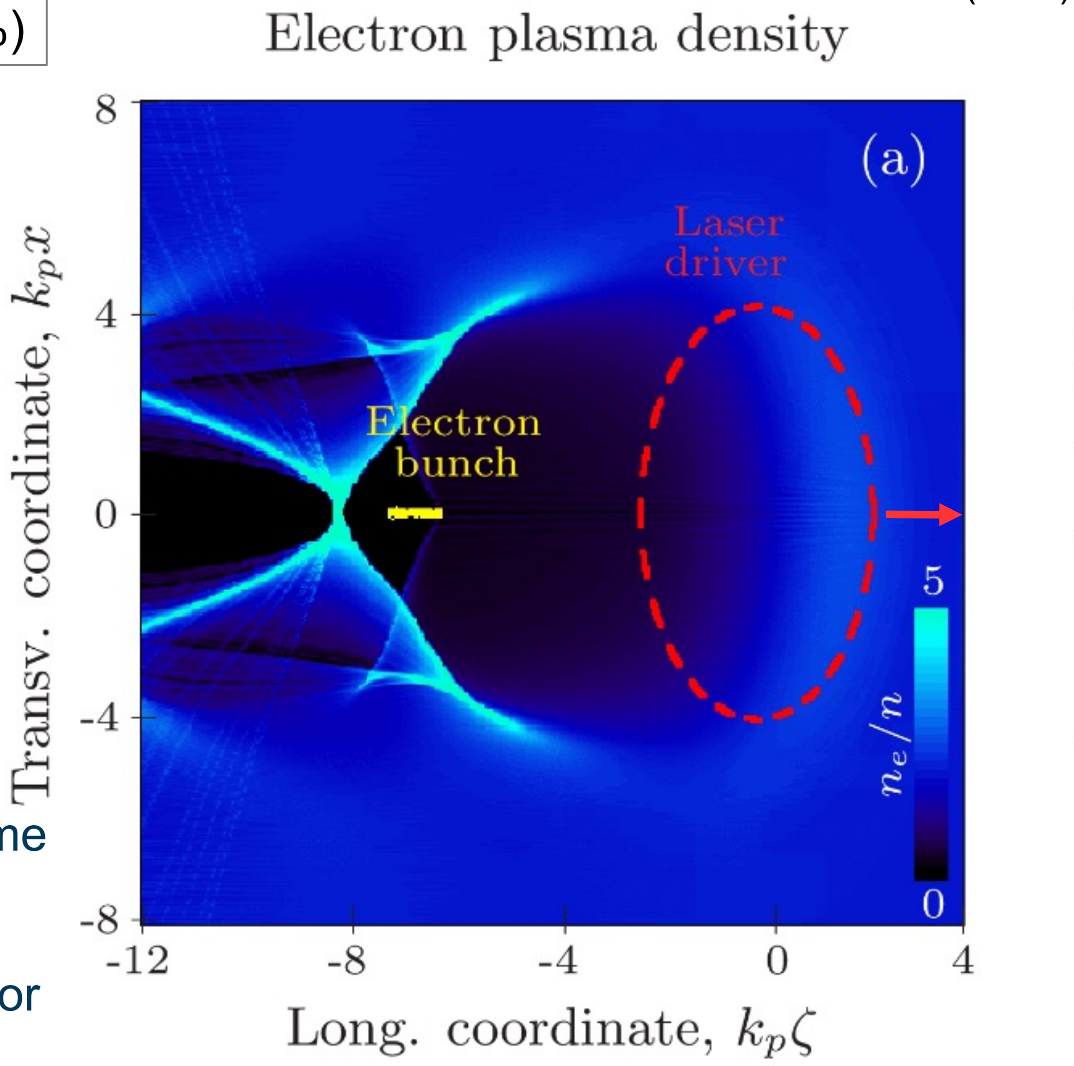
→ Not suitable for positron acceleration (diff eme required for positron arm, e.g et al., PRAB 2019)

See talk by S. Corde (Thu 9.30am)

→ Strong focusing yields small bunch size (~nm @ ~ TeV energies for collider-relevant emittances):

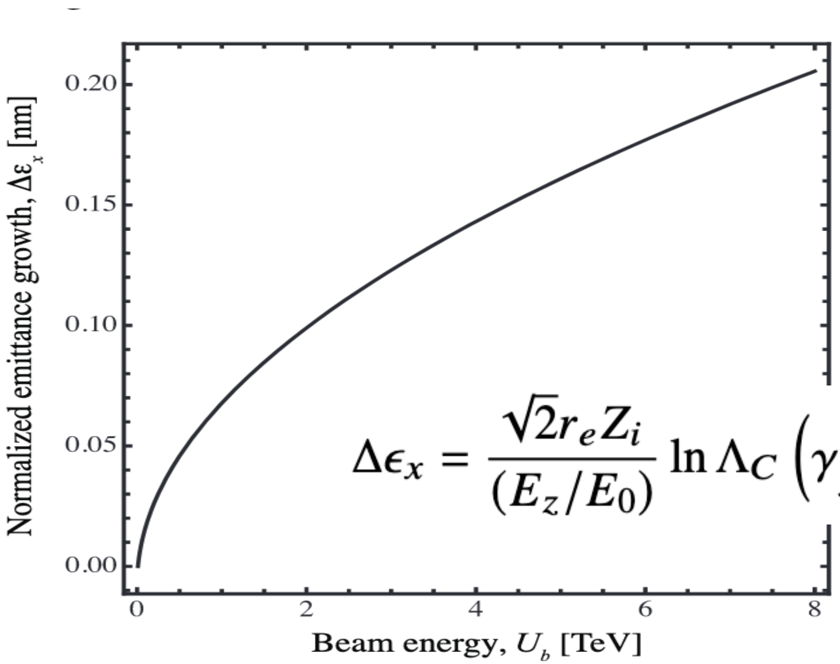
challenging for inter-stage transport and alignment!

Schroeder et al., JINST (2022)



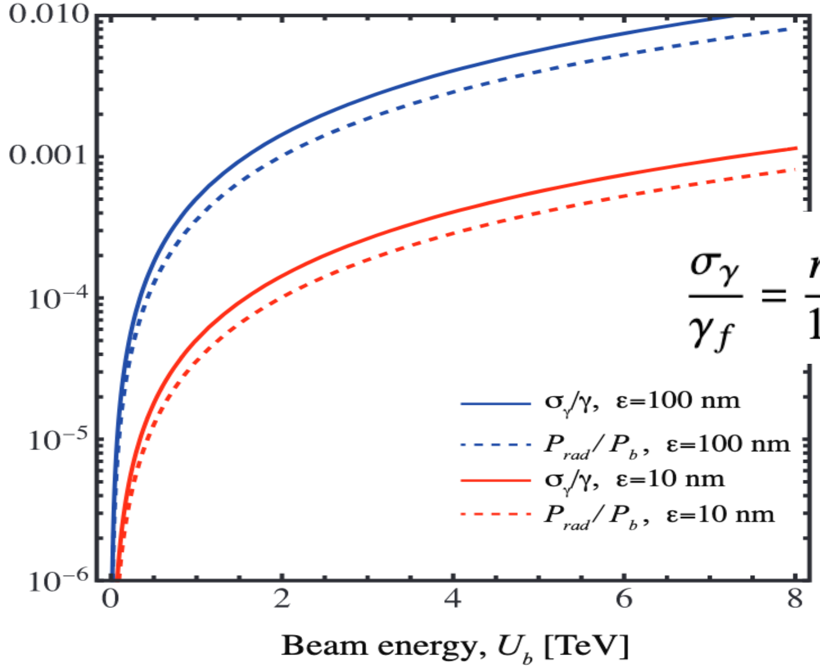
LPA stage in the bubble regime provides quality-preserving acceleration

- **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%**.



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

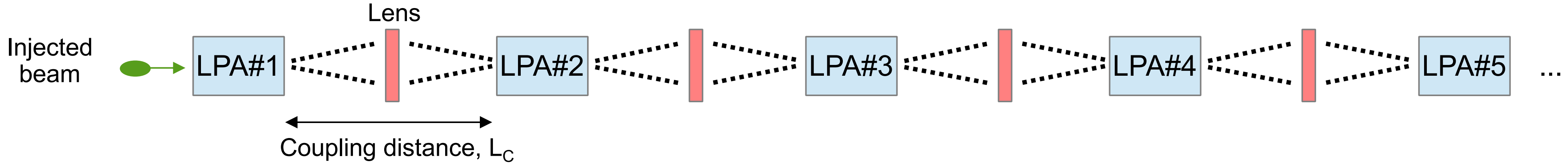
- **Transverse beam stability**:
  → beam hosing suppressed by spread in betatron frequency induced by background ion motion triggered by the high-charge, low-emittance, and high-energy beam;
  → beam emittance from ion motion suppressed by bunch tapering (n g).

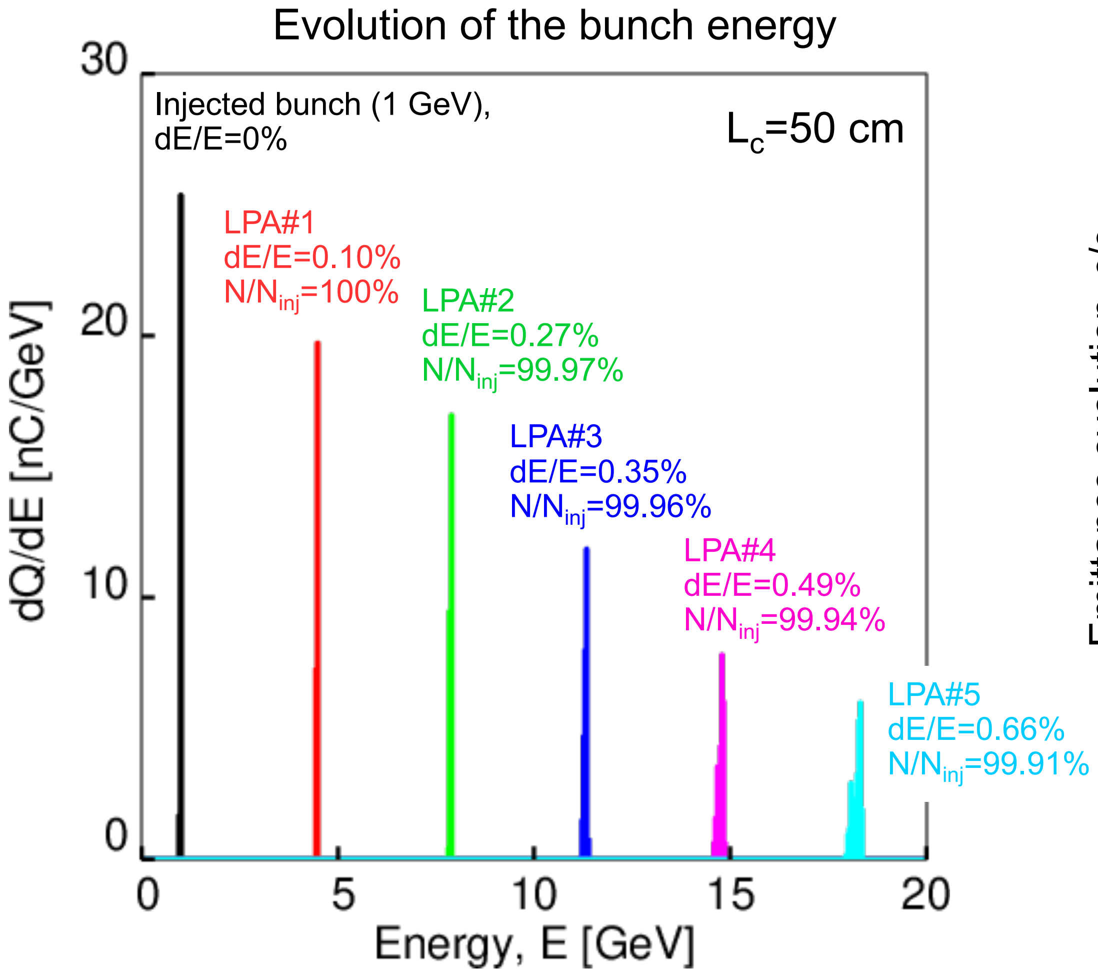
See talk by S. Diederich (Thu 9am)

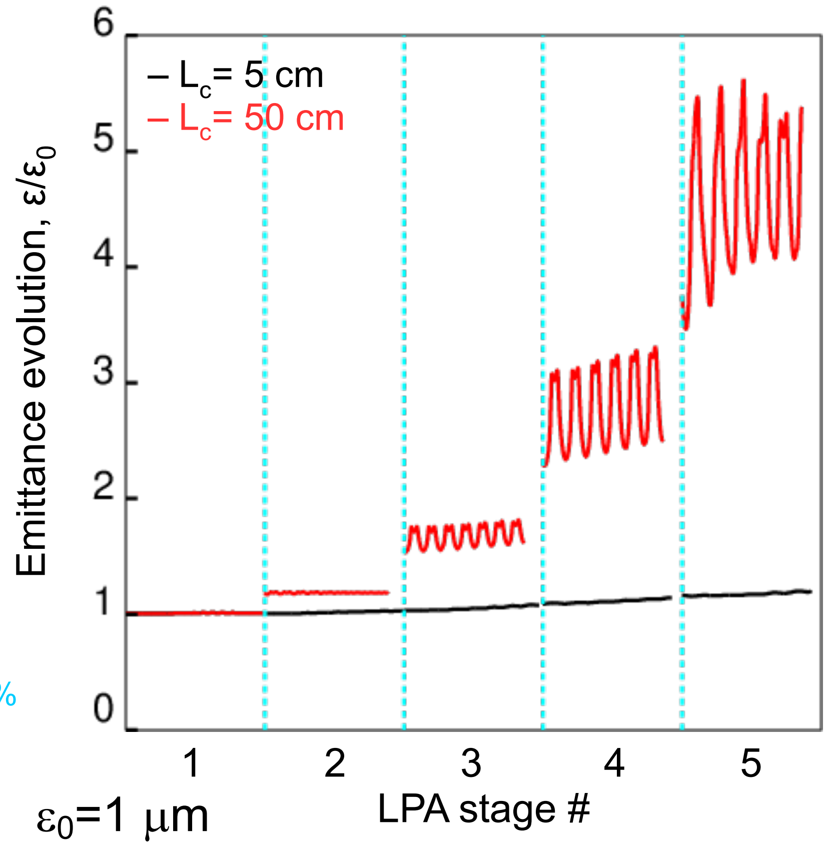
Mehrling et al., PRL (2018)
Benedetti et al, PRAB (2017)
Benedetti et al., Phys. Plasmas (2021)

Results assume round beam. **Flat could be prone to emittance mixing!**

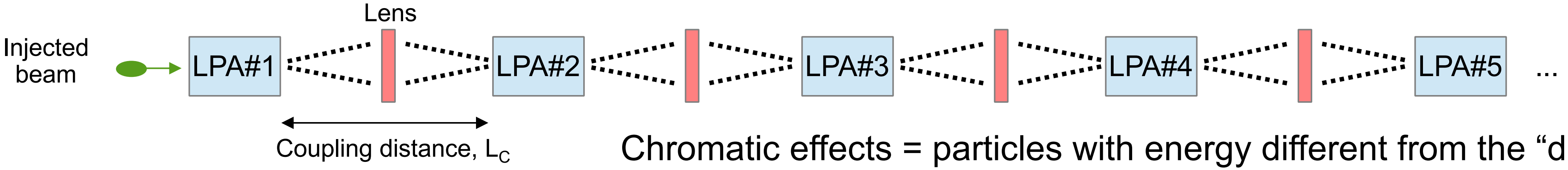
Emittance preservation requires development of achromatic inter-stage transport elements for e-beam





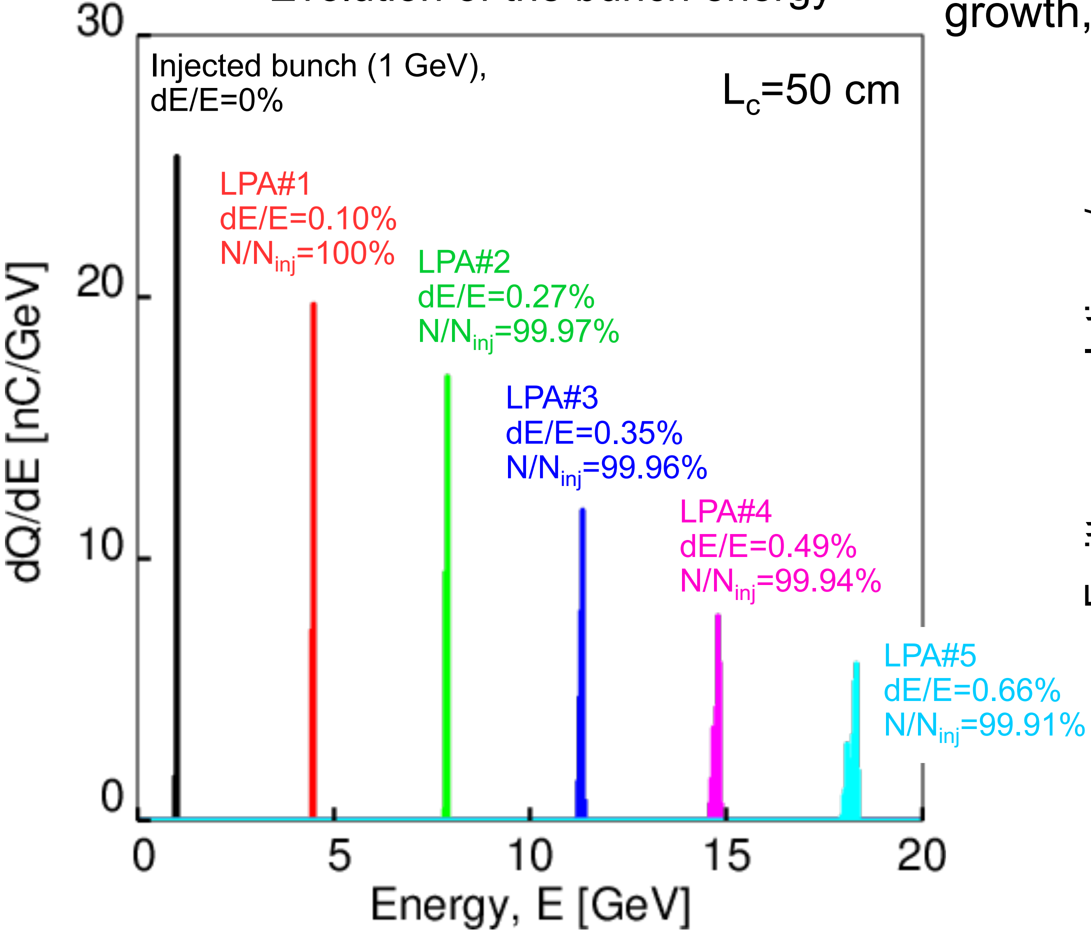


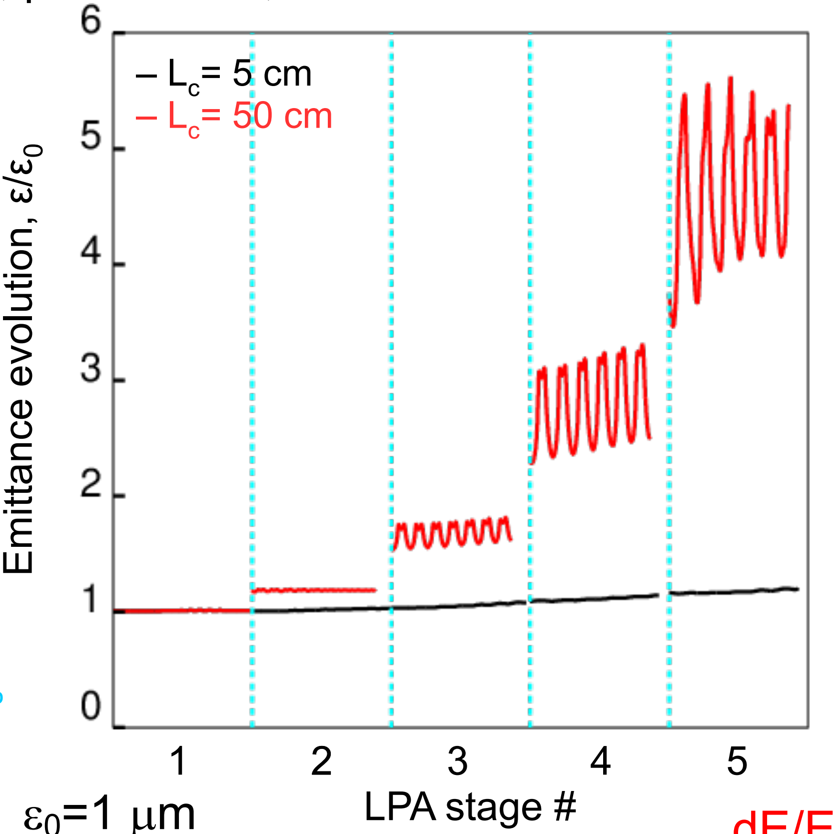
Emittance preservation requires development of achromatic inter-stage transport elements for e-beam



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:

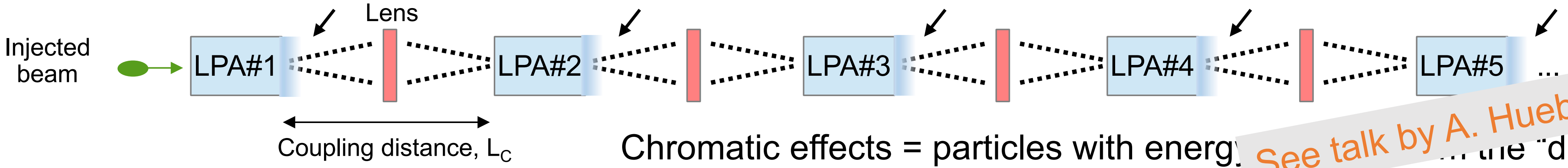
$$\boxed{\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}}$$

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 @ 1 TeV

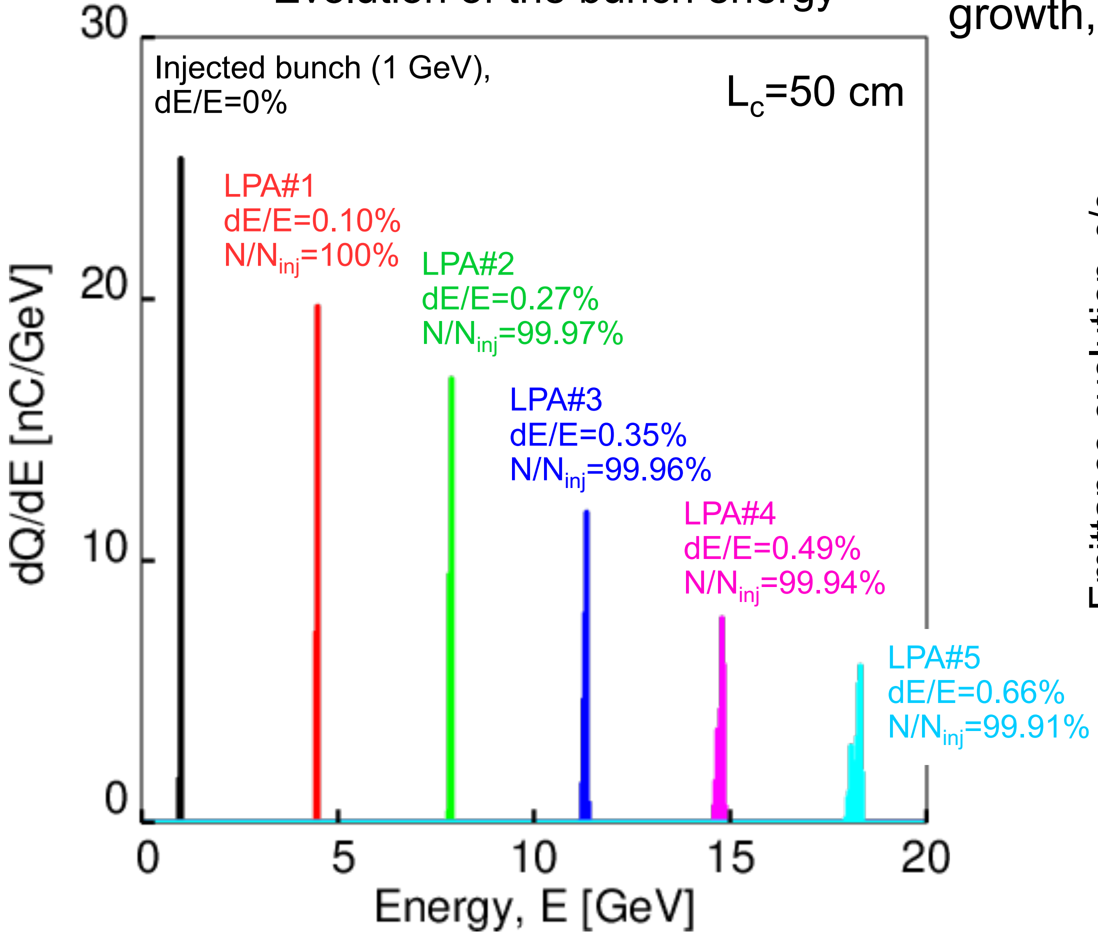
Emittance preservation requires development of achromatic inter-stage transport elements for e-beam

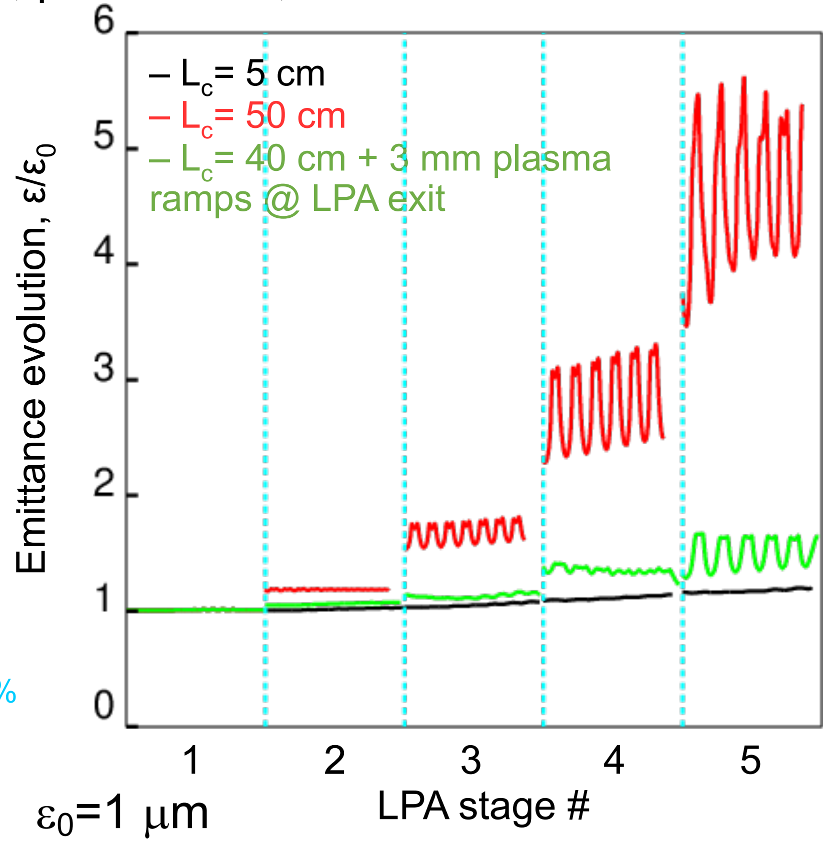


See talk by A. Huebl (Wed 3pm)

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

Evolution of the bunch energy





C. Lindstroem, PRAB (2021)

Emittance growth from chromaticity in drifts:

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

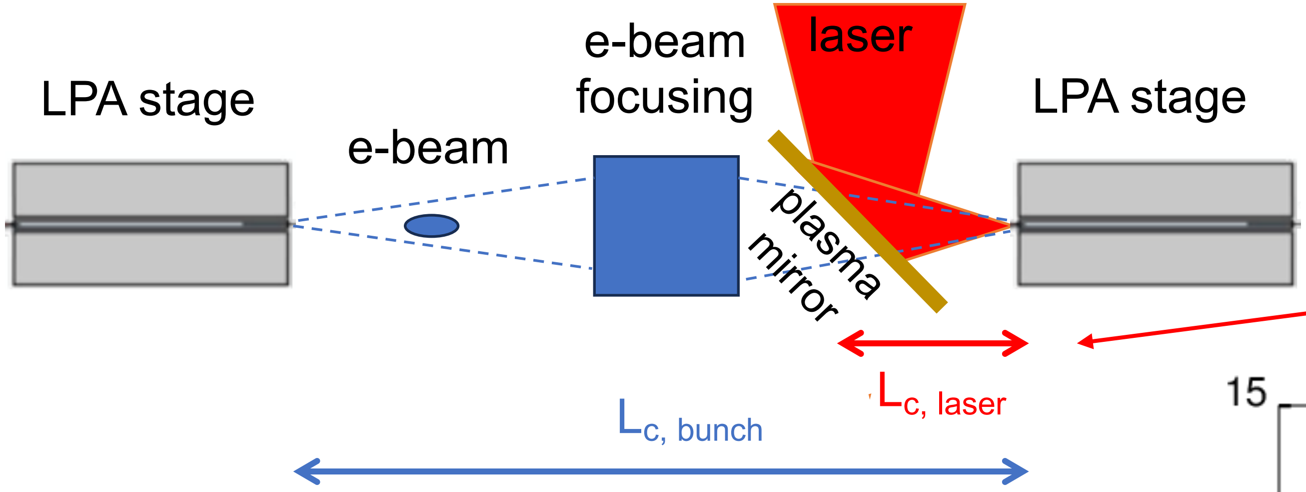
Exit ramp expands beam size preserving emittance (if $k_\beta L_{ramp} \gtrsim 1$): **$\varepsilon_0/\sigma_0$ decreases!**

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

- Ramps become (too) long at high energy
- Development of achromatic focusing optics (or with large chromatic acceptance) required

→ compactness challenging!

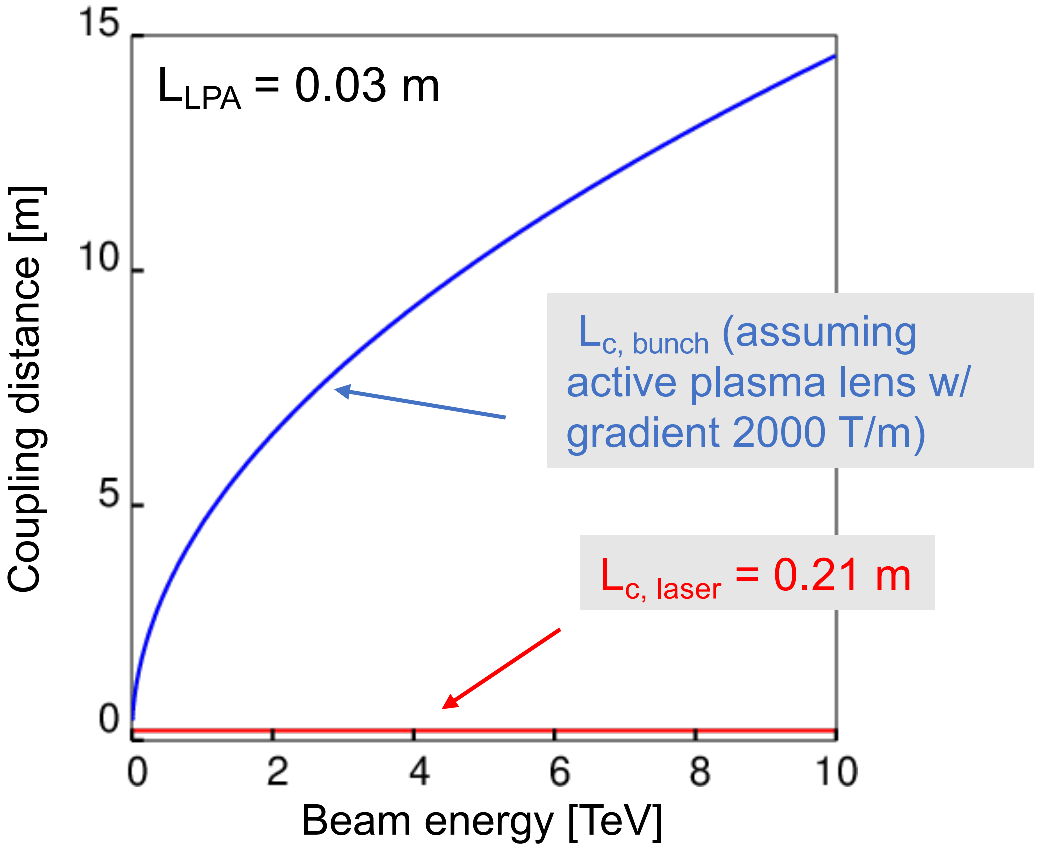
Minimum coupling distance between stages determined by refocusing of tightly-focused bunch (not laser in-coupling)



Determined by laser intensity @ plasma mirror (I_{pm}~10^{16} W/cm^2)

Determined by focusing gradient (~ fixed to its max value) and beam energy

→ $L_{c,\text{ bunch}} \sim \gamma^{1/2}$



$L_{c,\text{ bunch}}$ (assuming active plasma lens w/ gradient 2000 T/m)

$L_{c,\text{ laser}}$ = 0.21 m

→ Average gradient decreases with energy (LPA stages are further and further apart)

→ Focusing optics always needed for tightly focused bunches (ballistic transport possible above >44 TeV)

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:

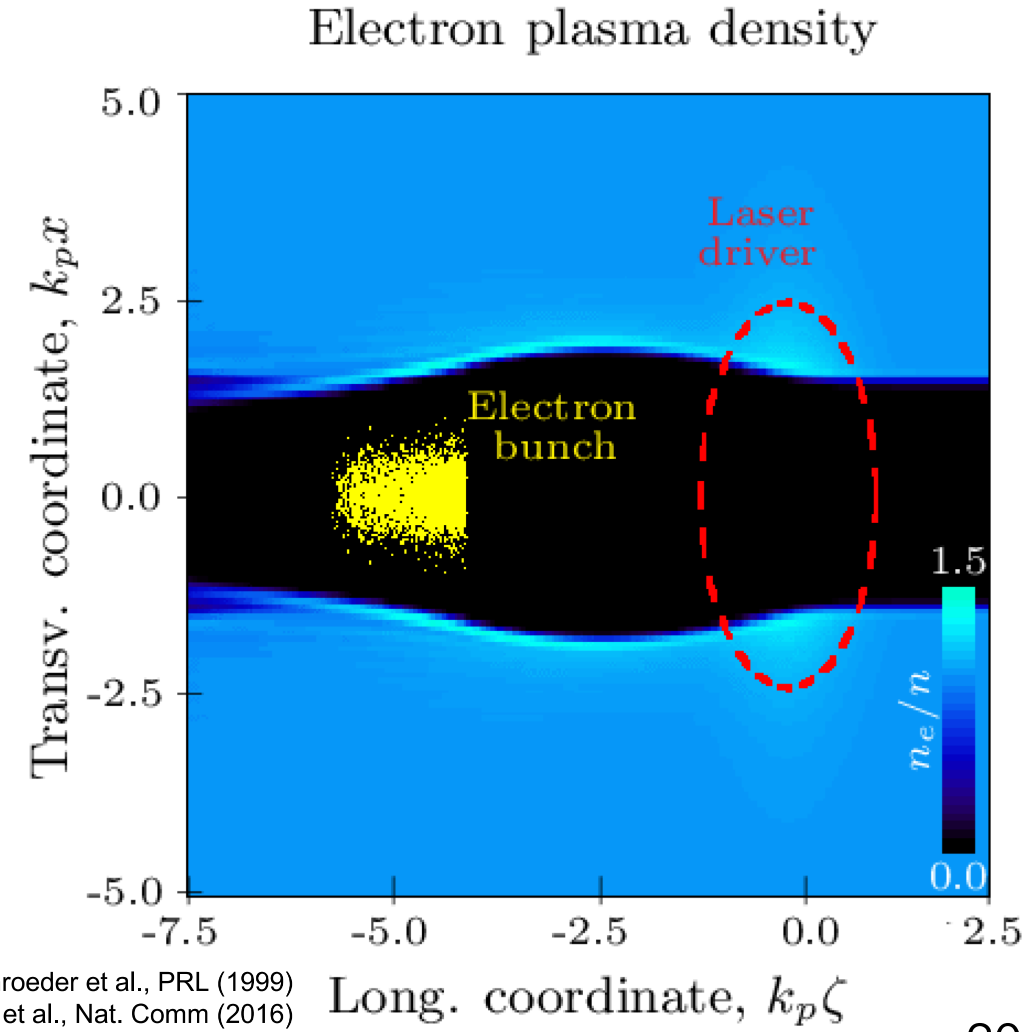
- Wake-to-bunch energy transfer = 68%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic

→ ~200 LPA stages/TeV + suitable for positron acceleration

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

→ Unstable w/o strong focusing: stabilization based on structured channel under investigation

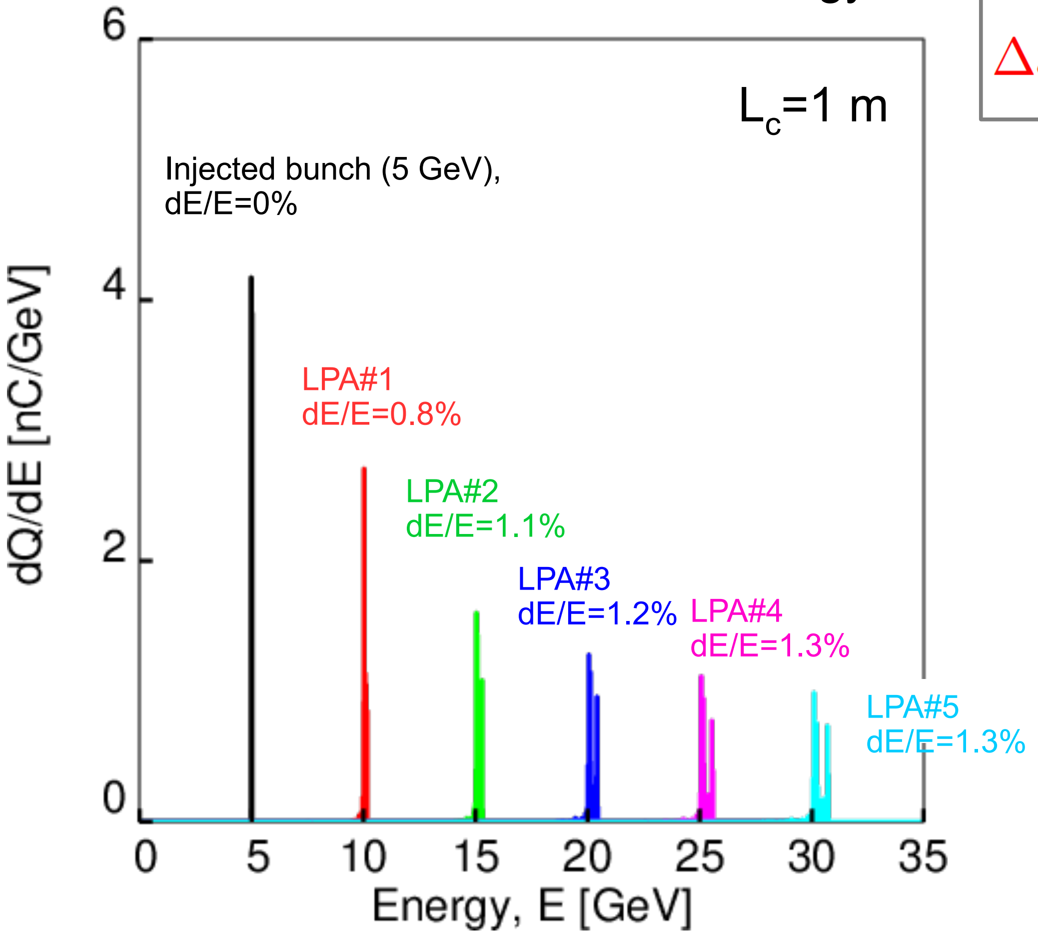
→ Hollow-channel allows for large (~um-scale) beam size: **relaxed constraints on inter-stage transport and alignment!**



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, relaxes alignment tolerances, and enables compact staging

Evolution of the bunch energy

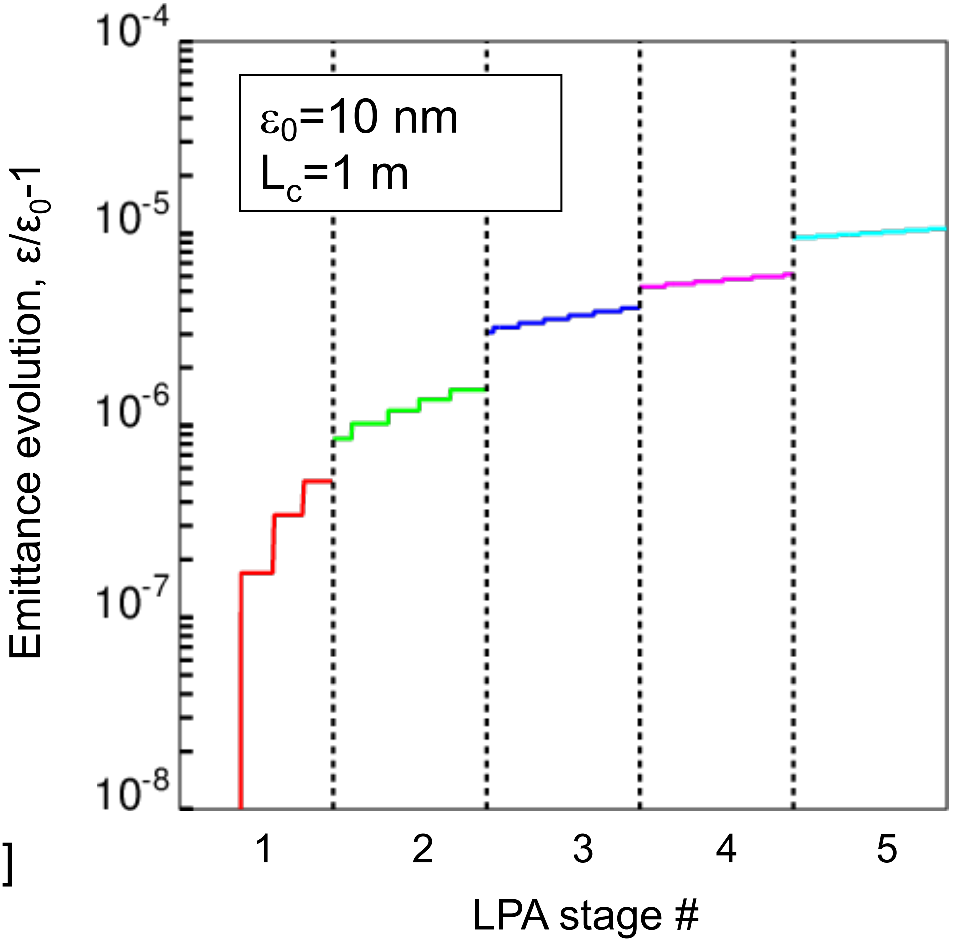


$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

For 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



Inter-stage: ballistic (no focusing)
[matching w/ conventional quadrupoles in <~ m scale distance possible]

Recap of LPA-based collider challenges and potential solutions (some requiring significant R&D)

- **Laser diffraction**

-Self-guiding in nonlinear regime
-Guiding in pre-formed plasma channel

- **Laser-particle beam dephasing**

-Plasma tapering

- **Laser energy depletion (with high gradient)**

-Staging with compact driver in-coupling

- **Positron focusing and acceleration (with high quality)**

-Use plasma columns/filaments
-Use hollow channels

- **High laser-to-beam efficiency (no energy spread growth)**

-Shaped particle beams
-Laser energy recovery

- **Heating of plasma**

-Use an “energy recovery” pulse

- **High-average laser power**

-Fiber laser combining

- **Scattering in plasma**

-Strong plasma focusing
-Use (near-) hollow channels

- **Emittance growth via ion motion**

-Use hollow channel
-Adiabatic, slice-by-slice, matching

- **Beamstrahlung mitigation**

-Short bunches
-Flat beams in hollow channels

- **Beam break-up / other transverse beam instabilities**

-Detune betatron freq. (e.g., ion motion or energy spread)
-Stagger tuning

- **Alignment tolerances in linac:**

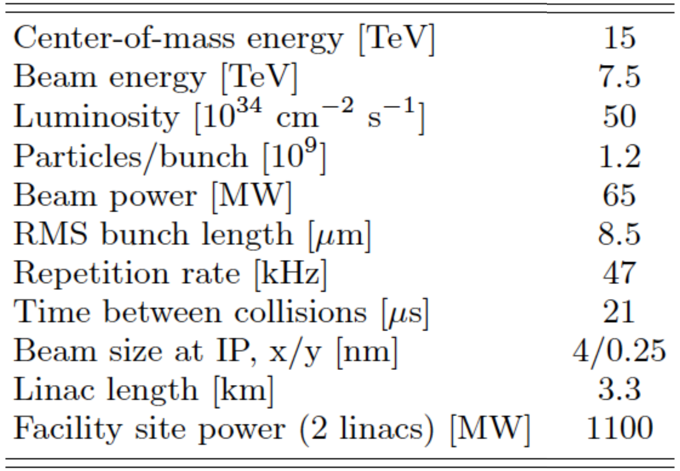
-Control beam size

- **Non-linac subsystems requiring (major) R&D:**

-beam (e+/e-) source (this could be laser-based)
-beam cooling
-polarization
-BDS, …

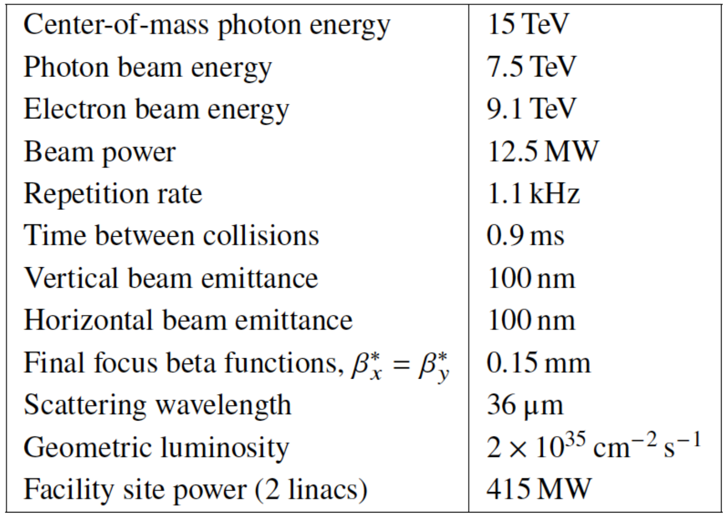
Summary and conclusions

High-level **e-/e+** collider parameters based on **hollow channel** LPAs



Center-of-mass energy [TeV]	15
Beam energy [TeV]	7.5
Luminosity [10^{34} cm^{-2} s^{-1}]	50
Particles/bunch [10^9]	1.2
Beam power [MW]	65
RMS bunch length [μm]	8.5
Repetition rate [kHz]	47
Time between collisions [μs]	21
Beam size at IP, x/y [nm]	4/0.25
Linac length [km]	3.3
Facility site power (2 linacs) [MW]	1100

High-level γ/γ collider parameters based on **bubble regime** LPAs



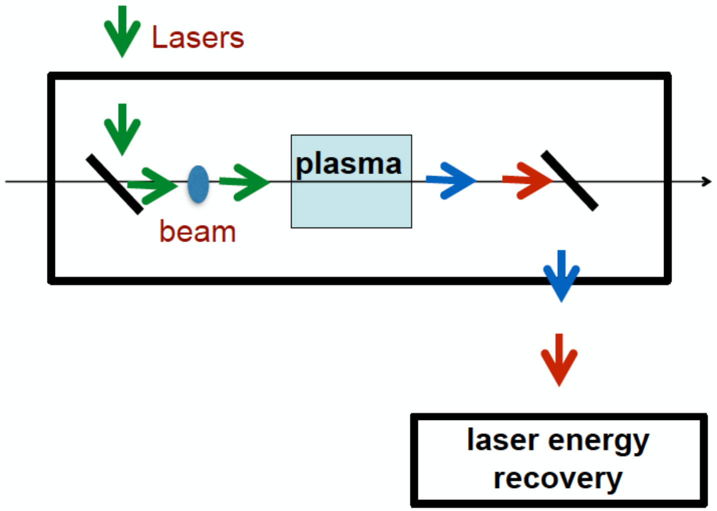
Center-of-mass photon energy	15 TeV
Photon beam energy	7.5 TeV
Electron beam energy	9.1 TeV
Beam power	12.5 MW
Repetition rate	1.1 kHz
Time between collisions	0.9 ms
Vertical beam emittance	100 nm
Horizontal beam emittance	100 nm
Final focus beta functions, $\beta_x^* = \beta_y^*$	0.15 mm
Scattering wavelength	36 µm
Geometric luminosity	2×10^{35} cm^{-2} s^{-1}
Facility site power (2 linacs)	415 MW

Schroeder *et al.*, JINST 18 T06001 (2023)

- Energy frontier particle physics community desires ~10 TeV pCM collider (P5 recommendation);
- LPAs potential candidates as drivers: high-gradient (relatively short linac), accelerate short bunches (saves power);
- Schematic for a LPA-based collider developed to guide R&D:
- Linac issues analyzed in this talk:
    - Characterization of LPAs operating in different regimes with fixed laser energy and wavelength (energy gain, optimal bunch current profile for high-efficiency and low-energy spread, tapering, etc.);
    - Designed collider-relevant LPA stages providing high-energy, high-efficiency, high-quality acceleration;
    - Emittance preservation during staging;
- Self-consistent design and integration of all sub-systems requires strong community effort (and $$).

Backup

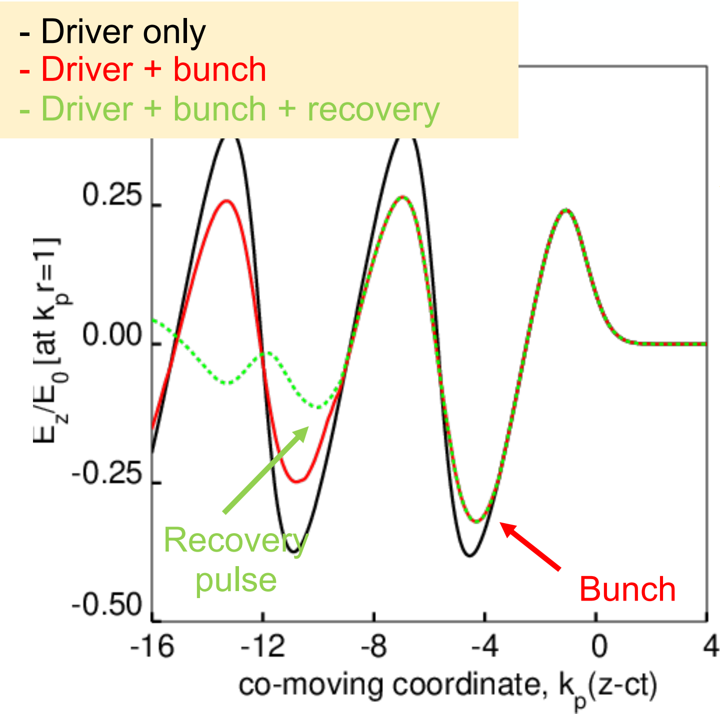
Wall-to-ebeam energy efficiency could be improved using a lower energy laser pulse to recover part of the unused energy in the plasma (and reduce heating of plasma)

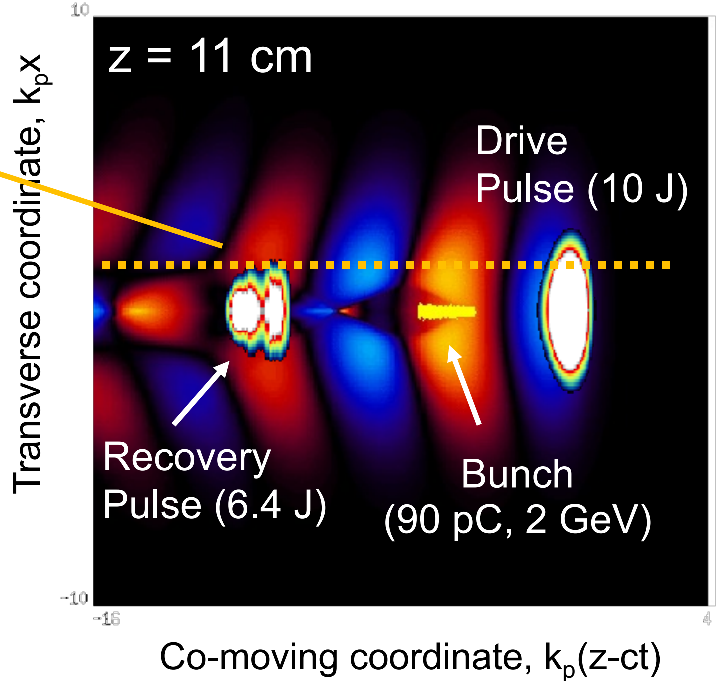


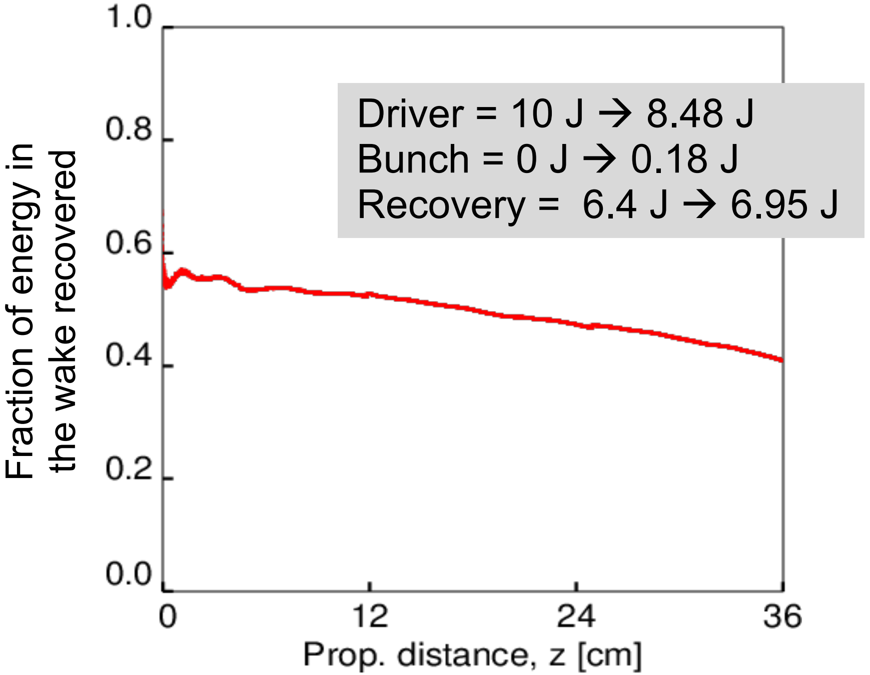
- Drive laser deposits energy into plasma wave (frequency red-shifts)
- Energy-recovery laser absorbs energy from wake(frequency blue-shifts)

→ Re-use laser in another LPA stage
→ Send to photovoltaic (targeted to laser wavelength) [**energy recovery**]
→ Reduce unused energy in the plasma [**heat management**]

Requires tuning of the LPA stage so energy absorption for bunch and recovery pulse is optimized. Presence/absence of actual Improvement depends on efficiencies (laser -> wake, wake->bunch, photovoltaic recovery, pulse creation)







Driver = 10 J → 8.48 J
Bunch = 0 J → 0.18 J
Recovery = 6.4 J → 6.95 J