INSTITUT POLYTECHNIQUE DE PARIS

[Cao et al., arXiv:2309.10495 (2023)](#)

arXiv > physics > arXiv:2309.10495

Physics > Accelerator Physics

[Submitted on 19 Sep 2023]

Positron Acceleration in Plasma Wakefields

G.J.Cao, C.A.Lindstrøm, E.Adli, S.Corde, S.Gessner

[Hue et al., PRR 3, 043063 (2021)](#)

PHYSICAL REVIEW RESEARCH **3**, 043063 (2021)

Efficiency and beam quality for positron acceleration in loaded plasma wakefields

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Acceleration of positrons in plasmas with high energy efficiency

Sébastien Corde
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Numerical simulations were performed using HPC resources from GENCI-TGCC (Grant No. 2020-A00080510786 and No. 2020-A00090510062) and using the open source quasistatic PIC code QuickPIC.

Outline

- Scientific context: beyond electron acceleration in blowout regime
  - ➢ Hosing for collider-type parameters
  - ➢ Not directly suited for positrons
- Quasilinear regime with a positron load
  - ➢ Efficiency
  - ➢ Evolution of transverse emittance
  - ➢ Uncorrelated energy spread
- Energy efficiency vs beam quality tradeoff
  - ➢ Quasilinear regime
  - ➢ Moderately nonlinear regime
  - ➢ Donut-shaped drivers
- The positron problem
  - ➢ Luminosity-per-power
  - ➢ Electron motion
  - ➢ Strategies

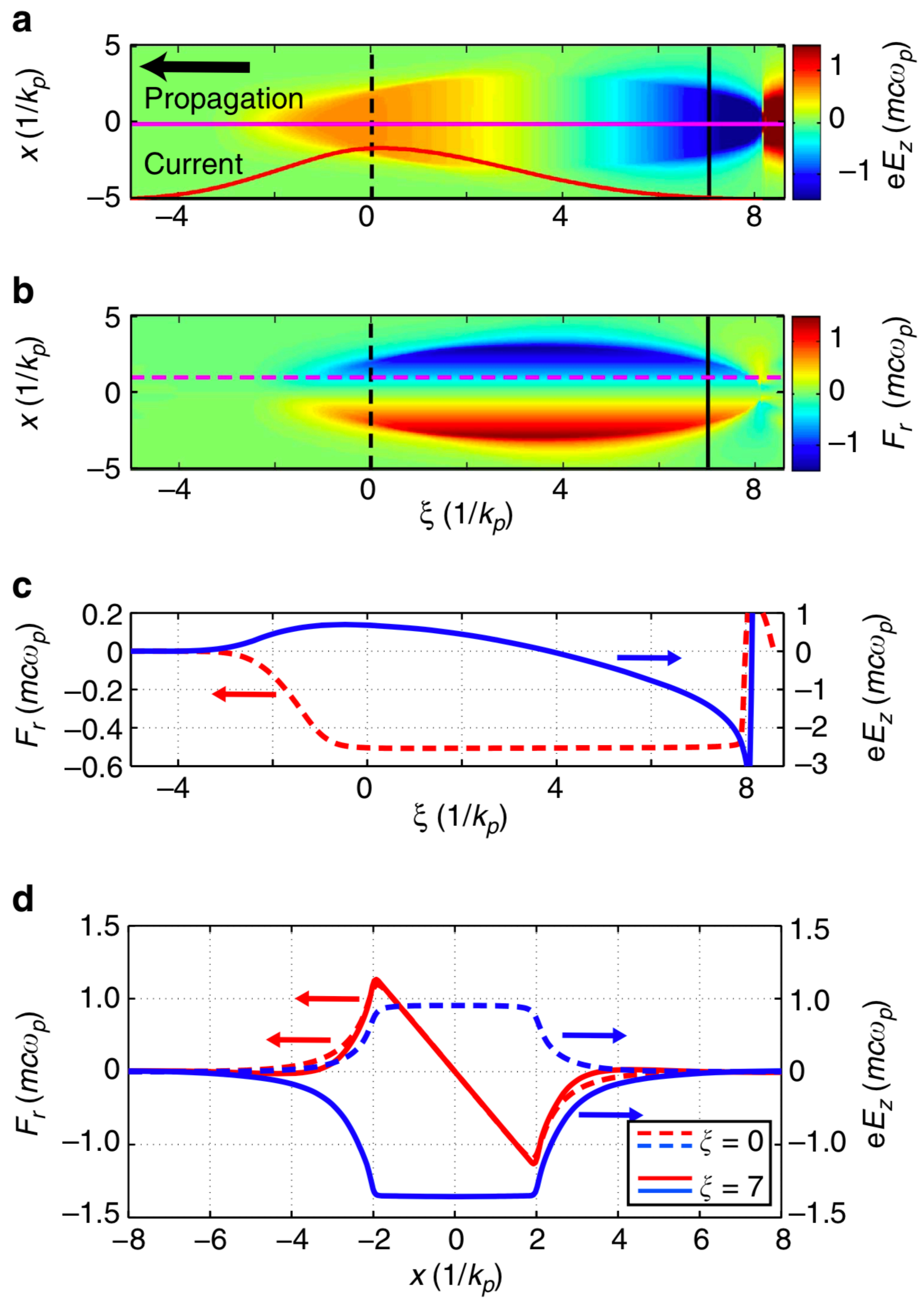
General remark: the discussion today will focus on PWFA, but is fully relevant to LWFA as well.

Scientific context

Beyond electron acceleration in the blowout regime

Scientific context: blowout as an ideal regime

Key properties of the blowout regime:



EM fields inside cavity:

$$\mathbf{E}/E_0 = \frac{1}{2}k_p\xi\ \mathbf{e}_z + \frac{1}{4}k_p r\ \mathbf{e}_r$$

$$c\mathbf{B}/E_0 = -\frac{1}{4}k_p r\ \mathbf{e}_\theta$$

Transverse force experienced by an e$^-$:

$$F_r = -e(E_r - cB_\theta) = -\frac{eE_0k_p}{2}r$$

⟶ Focusing force linear in *r*

Additional properties:

$$\partial_\xi F_r = 0 \qquad \partial_r F_z = 0$$

The blowout regime has ideal field properties for e$^-$:

- ⟶ emittance preservation is expected to be achievable.
- ⟶ beam loading allow for high efficiency, flat E_z field and therefore low energy spread.
- ⟶ most studied regime for electron acceleration, in both LWFA and PWFA.

Clayton et al., Nat Comm 7, 12483 (2016)

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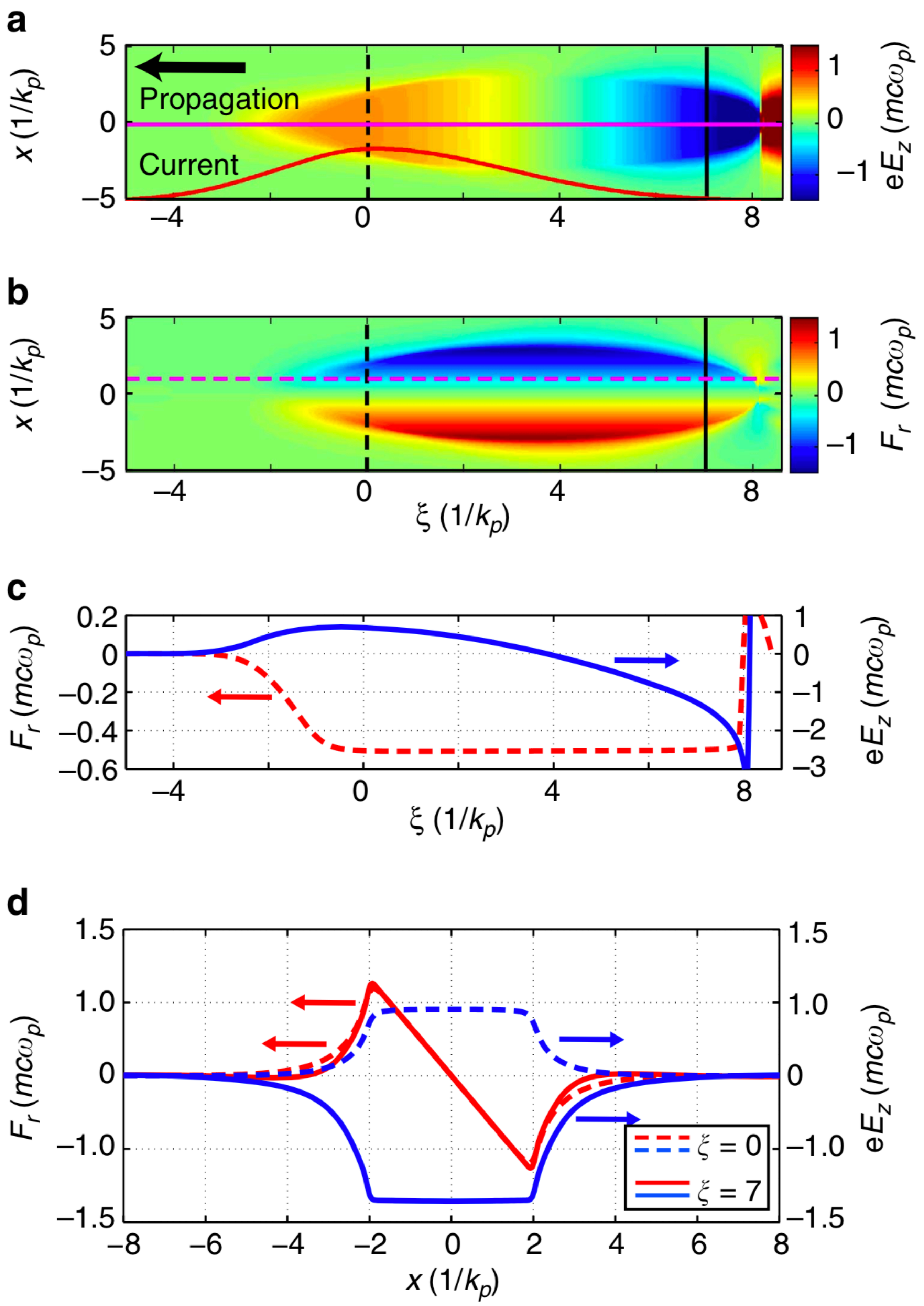

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But:

→ hosing instability may be an important limitation for collider beam parameters.

→ ion motion may lead to emittance growth.

→ what abut e^+?

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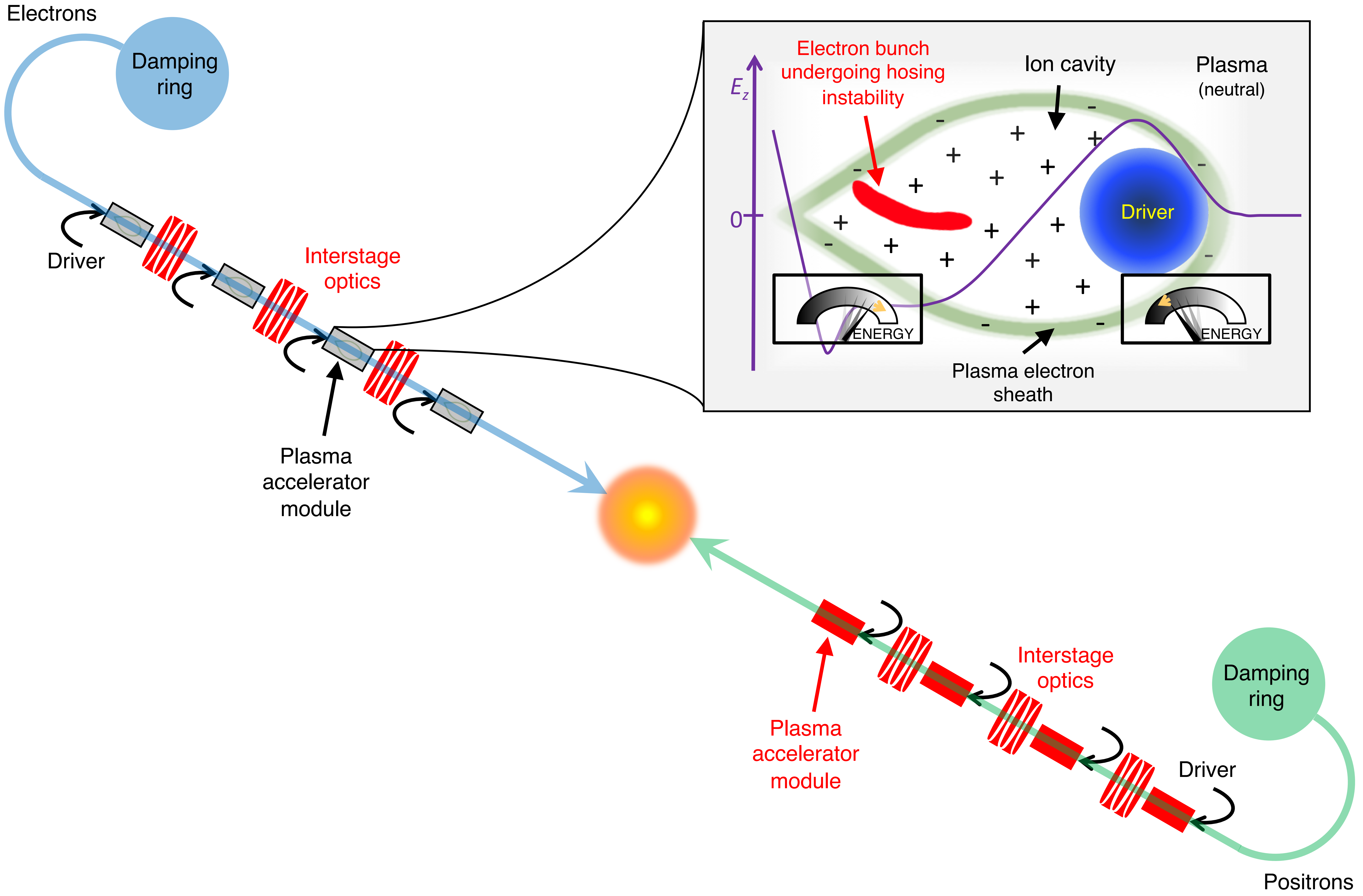
Scientific context: challenges



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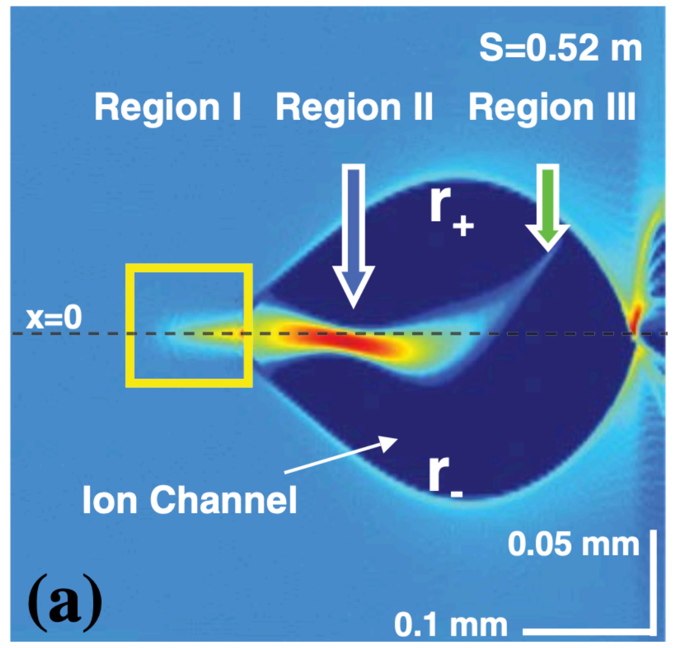
[Joshi, Corde and Mori, Phys. Plasmas 27, 070602 (2020)](#)

Scientific context: 1st motivation to go beyond blowout

Hosing/beam break-up instability



$$(\partial_\tau^2 + \omega_\beta^2)x_b = \omega_\beta^2 x_c$$

$$(\partial_\xi^2 + c_r c_\psi k_p^2/2)x_c = c_r c_\psi k_p^2 x_b/2$$

$$\tilde{x}_b \propto \exp(a\xi^{2/3}\tau^{1/3})$$

→ exponential growth of betatron oscillations can lead to beam breakup

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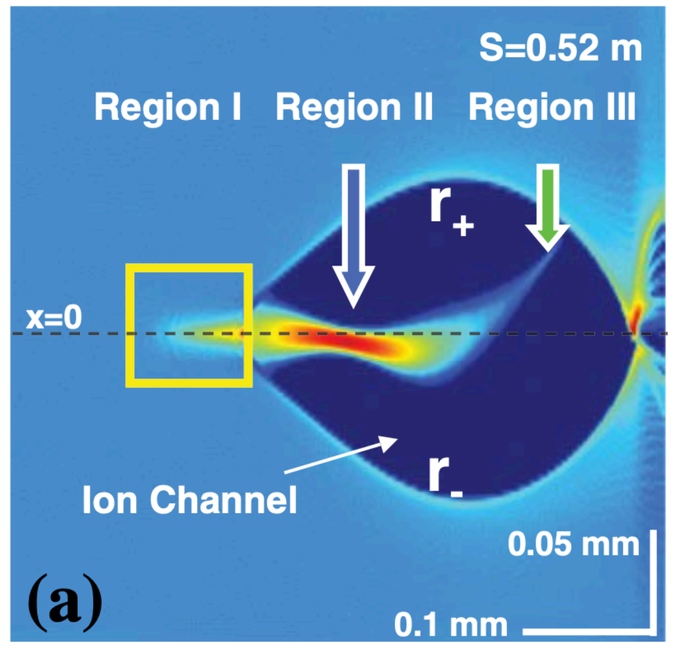

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Efficiency vs instability relation

$$\frac{\text{wake-deflecting force}}{\text{focusing force}} \simeq \frac{\eta_{p\to t}^2}{4(1-\eta_{p\to t})}$$

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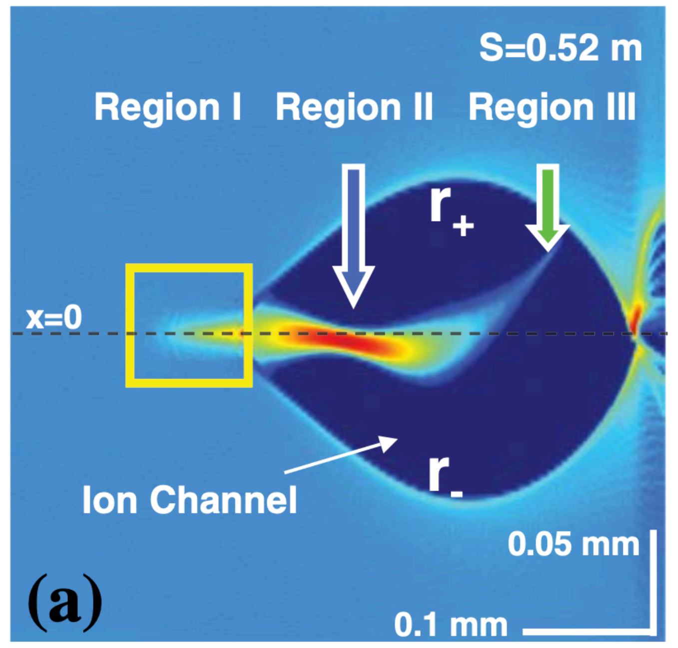

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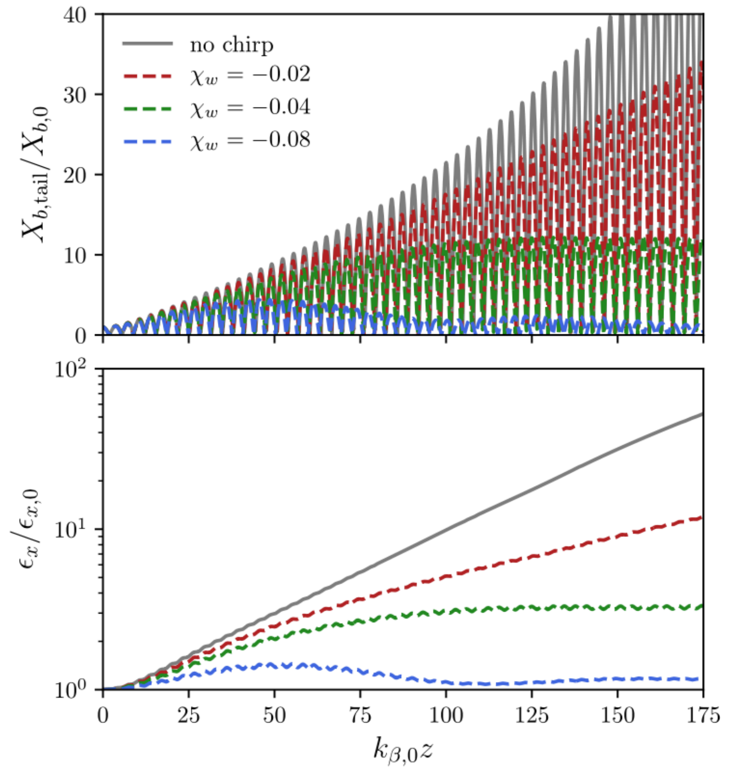

Energy chirp to mitigate hosing is too large to be realistic?

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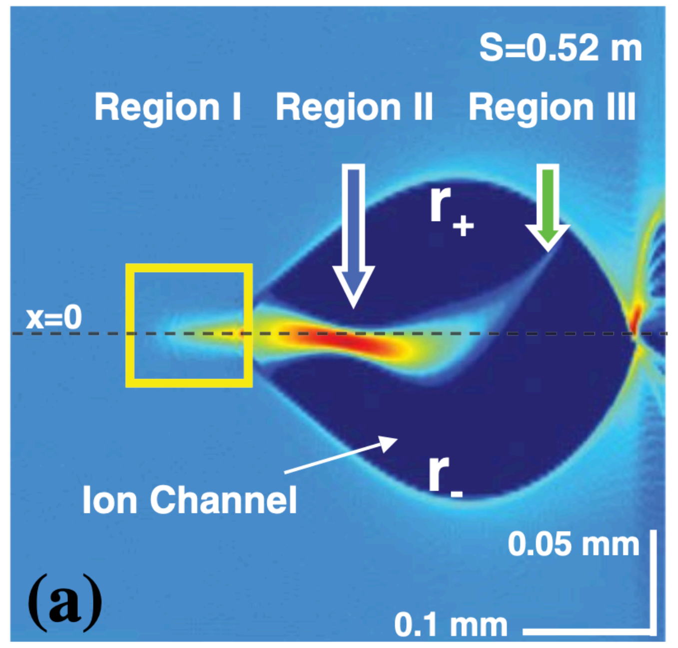

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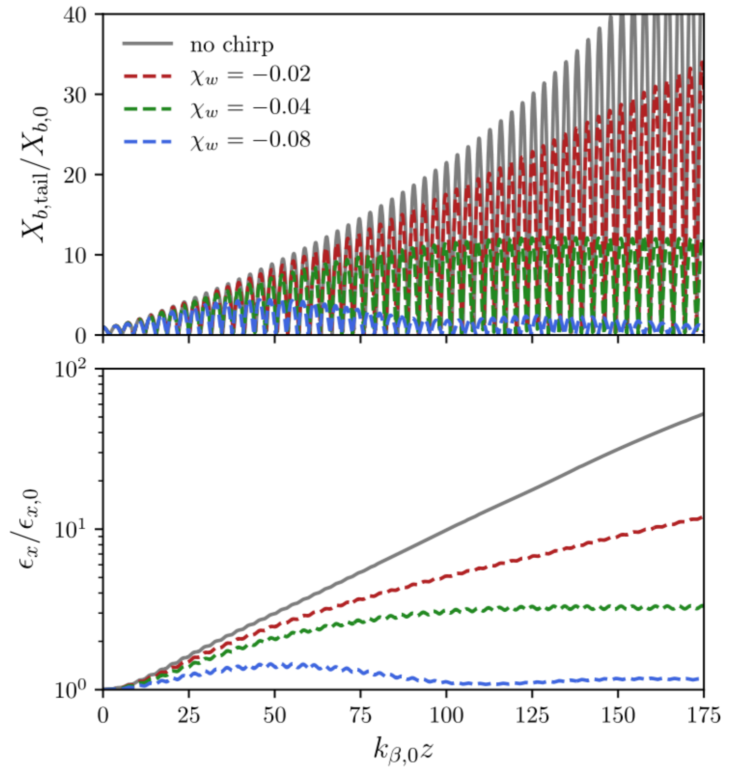

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Possible solutions:

- Ion-motion induced head-to-tail decoherence [Mehrling et al., PRL 121, 264802 (2018)]
- Use quasilinear regime with head-to-tail variation of focusing force [Lehe et al., PRL 119, 244801 (2017)]

→ need to look at the physics beyond idealised blowout

Scientific context: 2nd motivation to go beyond blowout

Accelerating positrons in plasma?

Plasma acceleration for an advanced linear collider? Positrons strongly desired, but:

« The most outstanding problem is the acceleration of positrons with bunch brightness, required for a linear collider » [Lebedev *et al.*, World Sci. (2016)].

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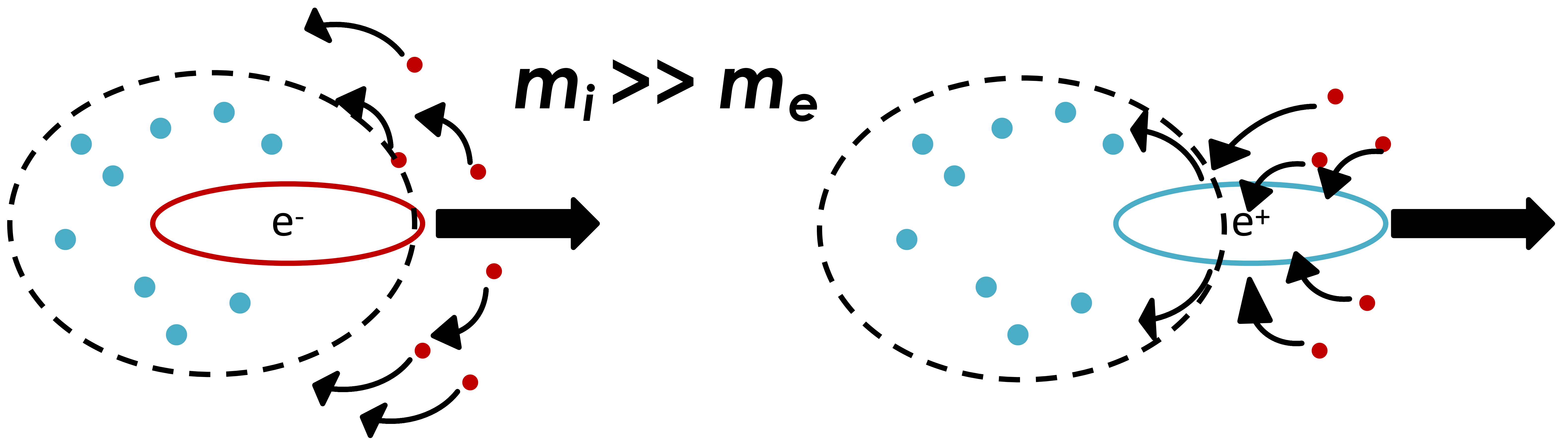

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Charge symmetry is broken in the nonlinear regime.

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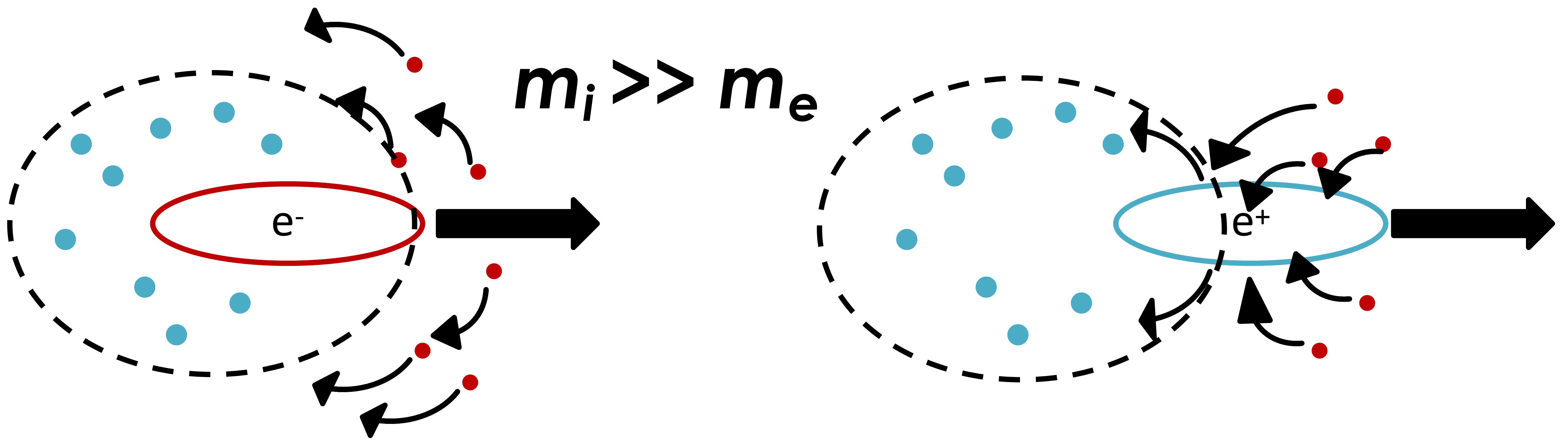

Plasma electrons are mobile but ions are not.

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Possible solutions:

- Quasilinear regime and a wealth of advanced regimes varying beam and plasma geometries, typically with plasma e^- flowing through the e^+ bunch.

→ need to look at the physics beyond idealised blowout

Quasilinear regime with a positron load

Efficiency in quasilinear regime

Energy efficiency from plasma to accelerated trailing bunch

$$\eta_{p\to t} = \frac{W_{\text{gain}}}{W_{\text{loss}}} = \left| \frac{N_t \langle E_z \rangle_t}{N_d \langle E_z \rangle_d} \right|$$

→ short bunches, linear and 1D

$$\eta_{p\to t,\text{1D linear}} = \frac{N_t}{N_d}\left(2 - \frac{N_t}{N_d}\right)$$

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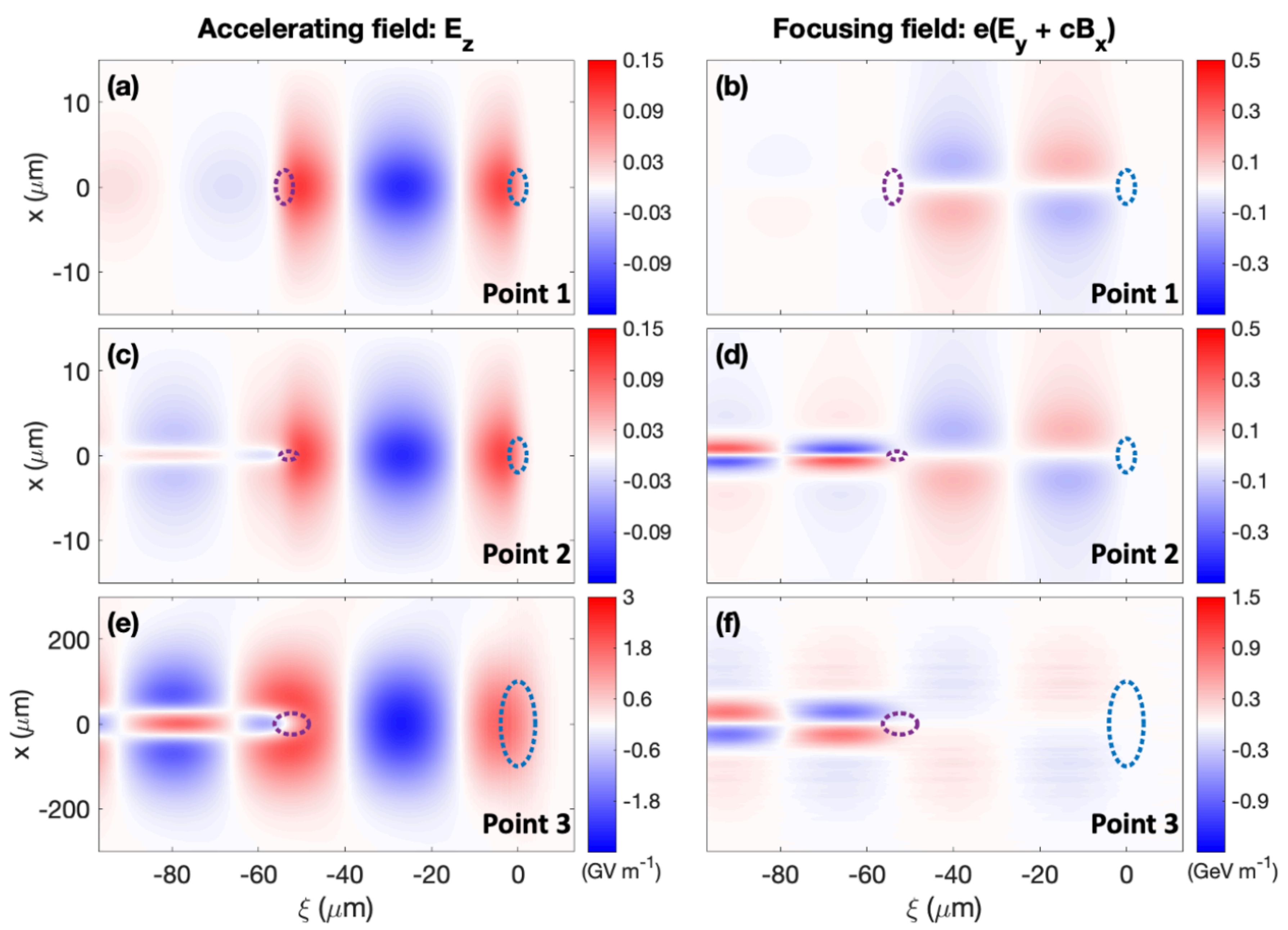
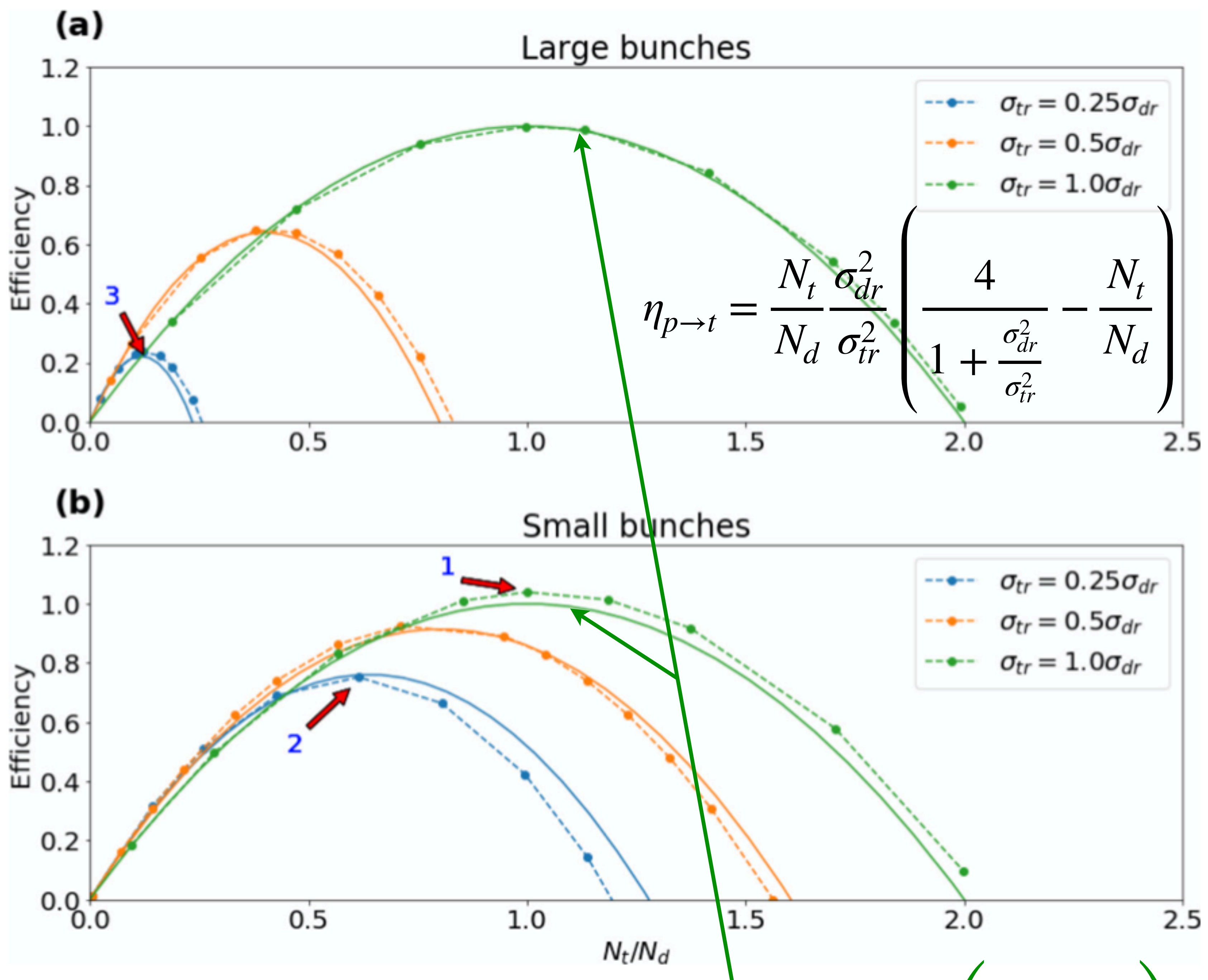
Linear 3D case:



- Same shape for drive and trailing bunches: linear 3D = linear 1D.



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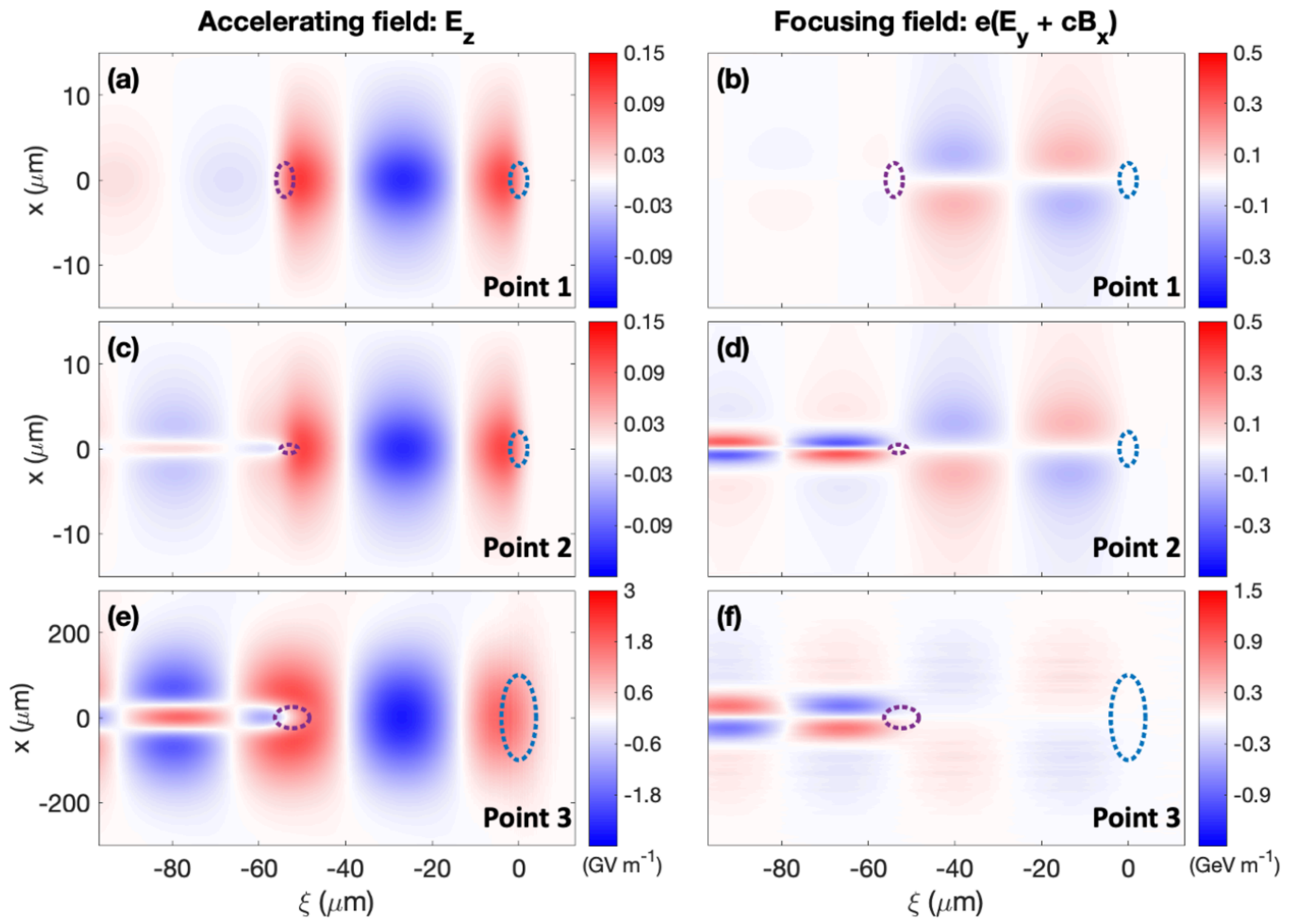

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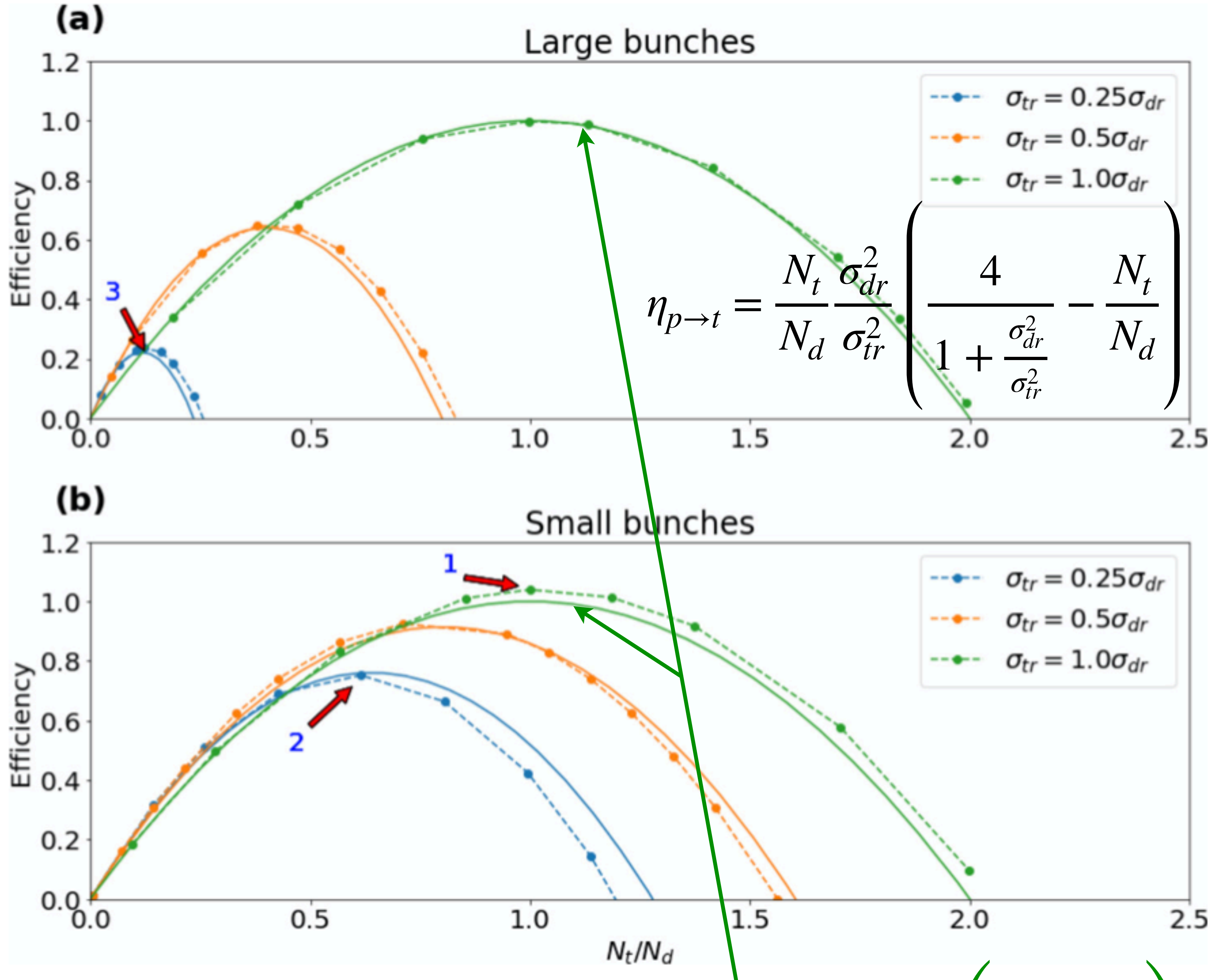

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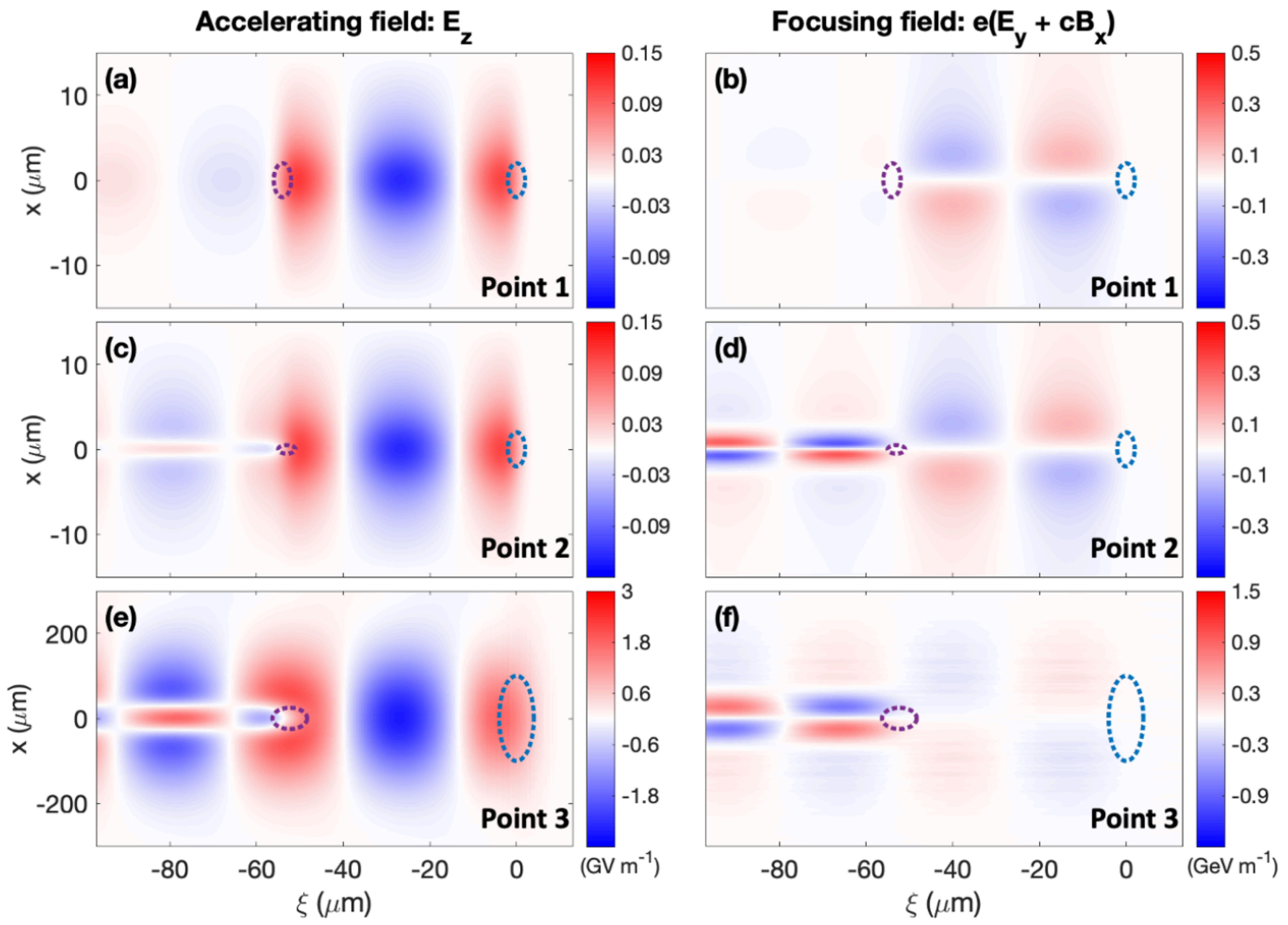
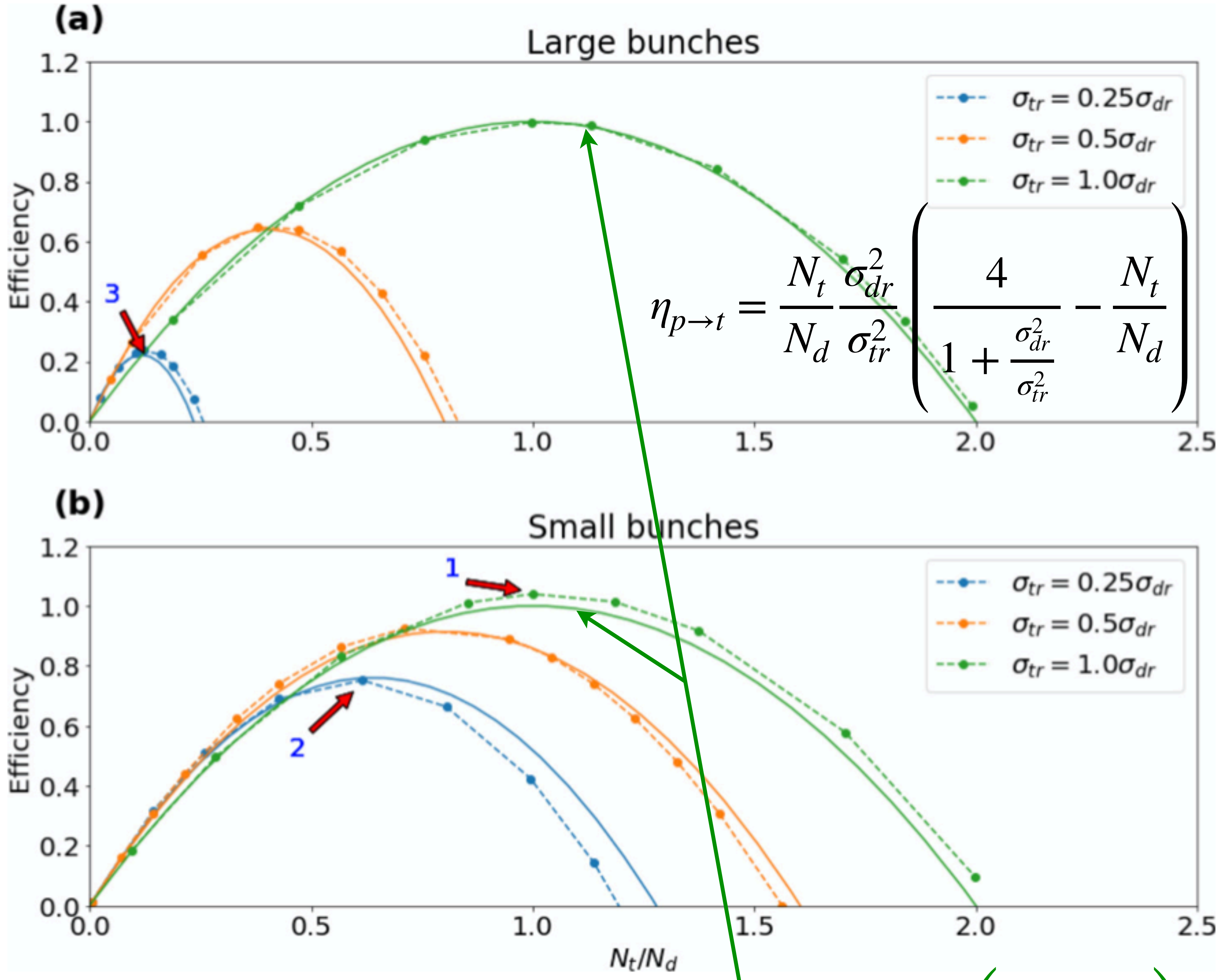


- Same shape for drive and trailing bunches: linear 3D = linear 1D.
- Highest efficiency: smallest fields left behind
- Small beams ($k_p\sigma_r \ll 1$) are much better because the fields extend over a plasma skin depth regardless of beam size



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Transverse emittance in quasilinear regime

Evolution of transverse emittance

Quasi-matching/transverse equilibrium:

$F_x \simeq -gx$ with g the gradient of the focusing force,

Enveloppe equation: $$\frac{d^2\sigma_x}{dz^2} = -k_\beta^2\sigma_x + \frac{\varepsilon^2}{\sigma_x^3} \quad \text{with} \quad k_\beta = \sqrt{g/\gamma m_e c^2}$$

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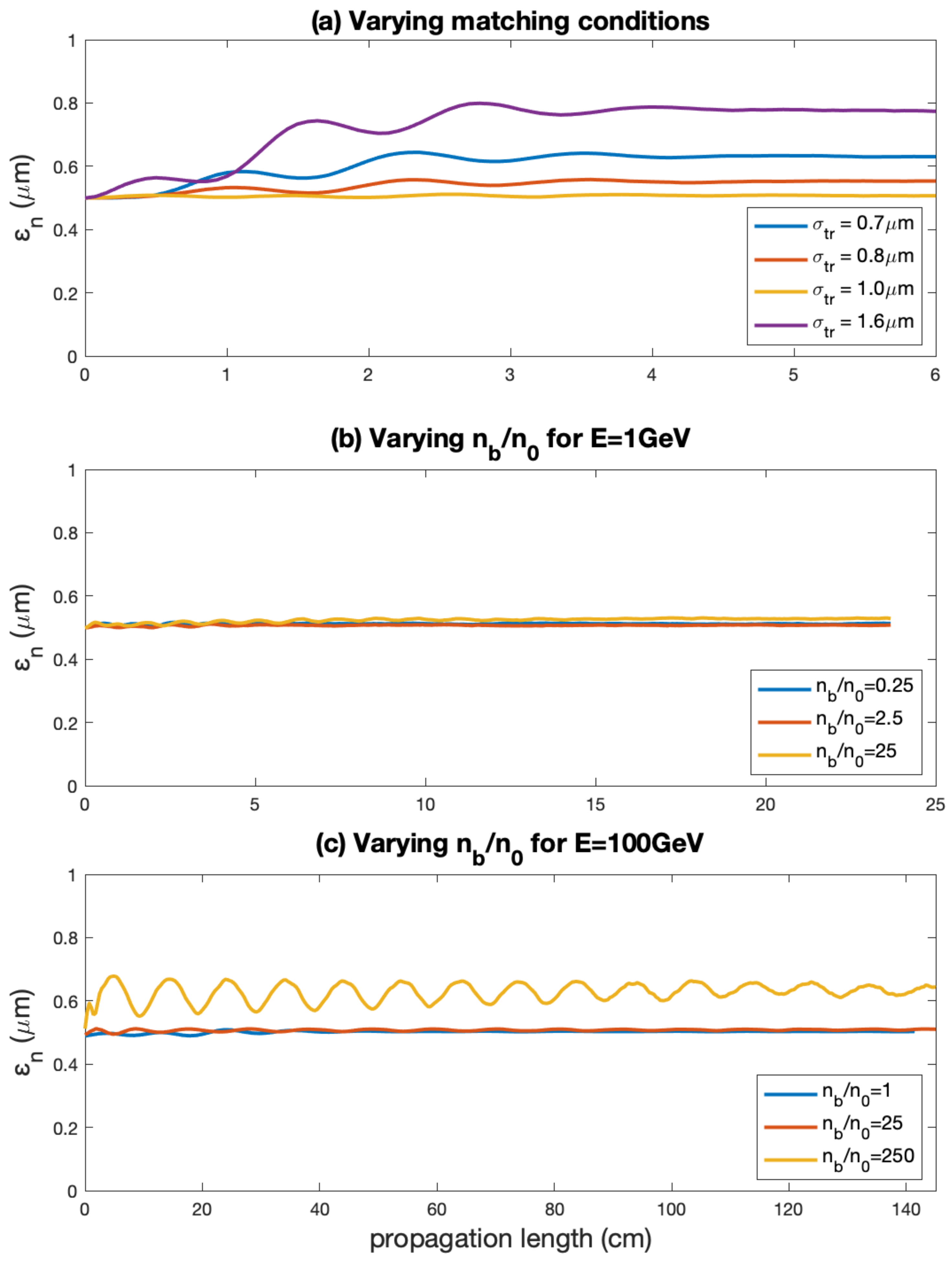

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	0.7	0.5	0.20	2.14	1	0.09	1	0.30	27.6
	0.8	0.5	0.26	2.14	1	0.09	1	0.39	11.6
Fig. 3(a)	1.0	0.5	0.40	2.14	1	0.09	1	0.61	1.74
	1.6	0.5	1.02	2.14	1	0.09	1	1.55	55.4
	1.01	0.5	0.41	2.14	0.25	0.045	1	0.16	1.74
Fig. 3(b)	1.00	0.5	0.40	2.14	2.5	0.14	1	1.52	2.64
	0.80	0.5	0.26	2.14	25	0.45	1	9.15	5.83
	0.327	0.5	4.28	2.14	1	0.09	100	0.07	2.73
Fig. 3(b)	0.288	0.5	3.33	2.14	25	0.45	100	1.63	3.67
	0.189	0.5	1.43	2.14	250	1.4	100	5.24	30.0

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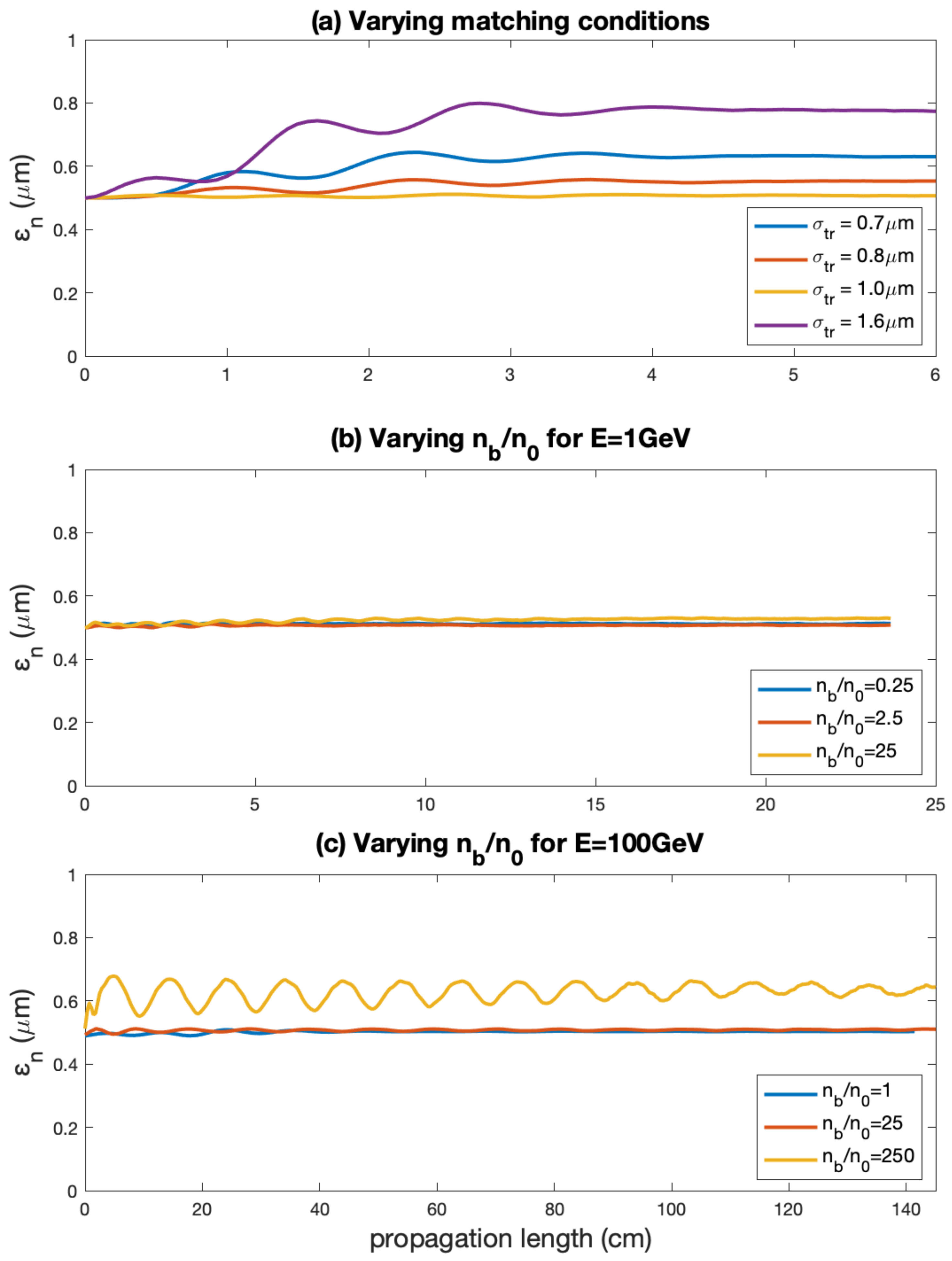

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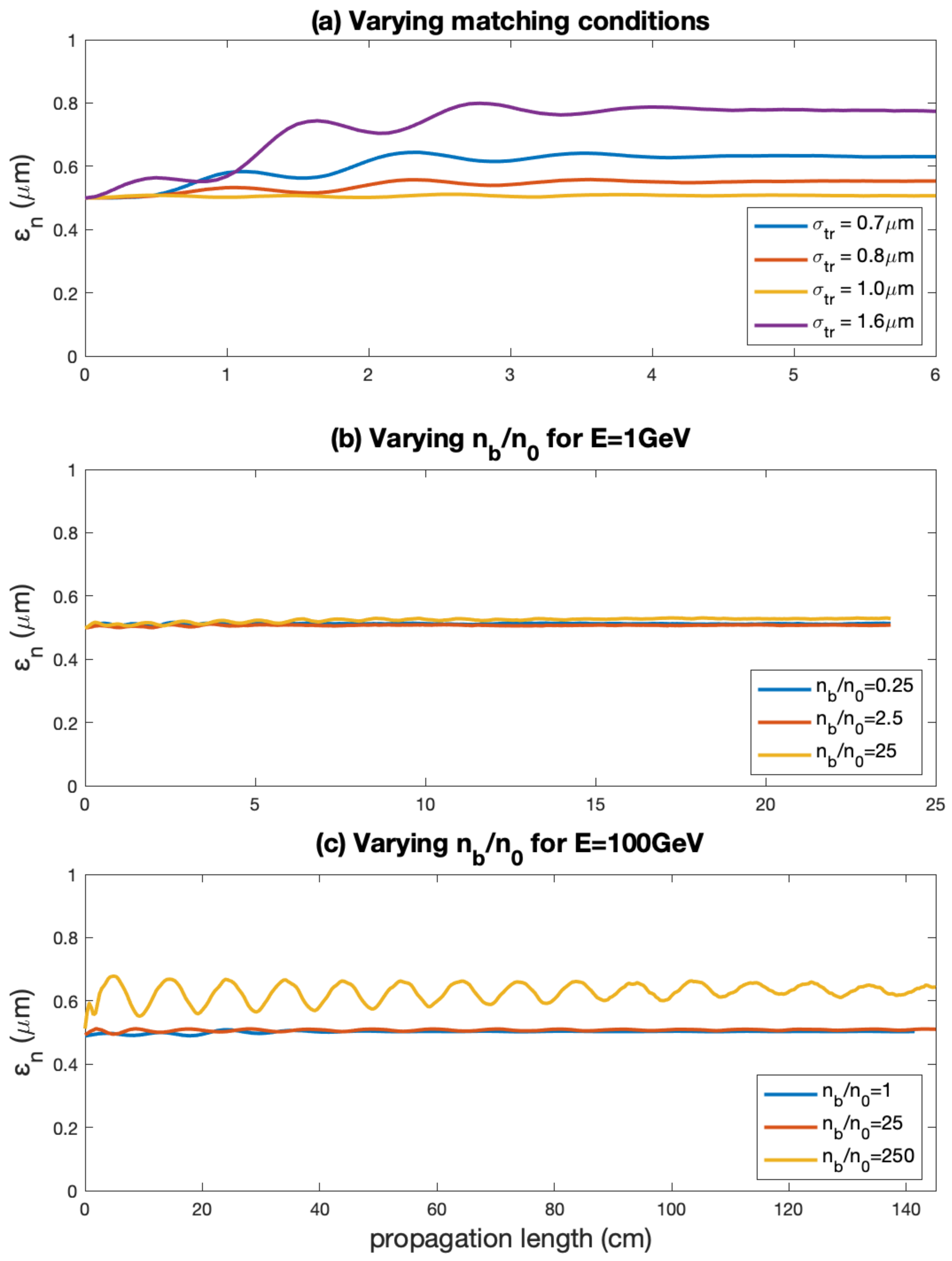

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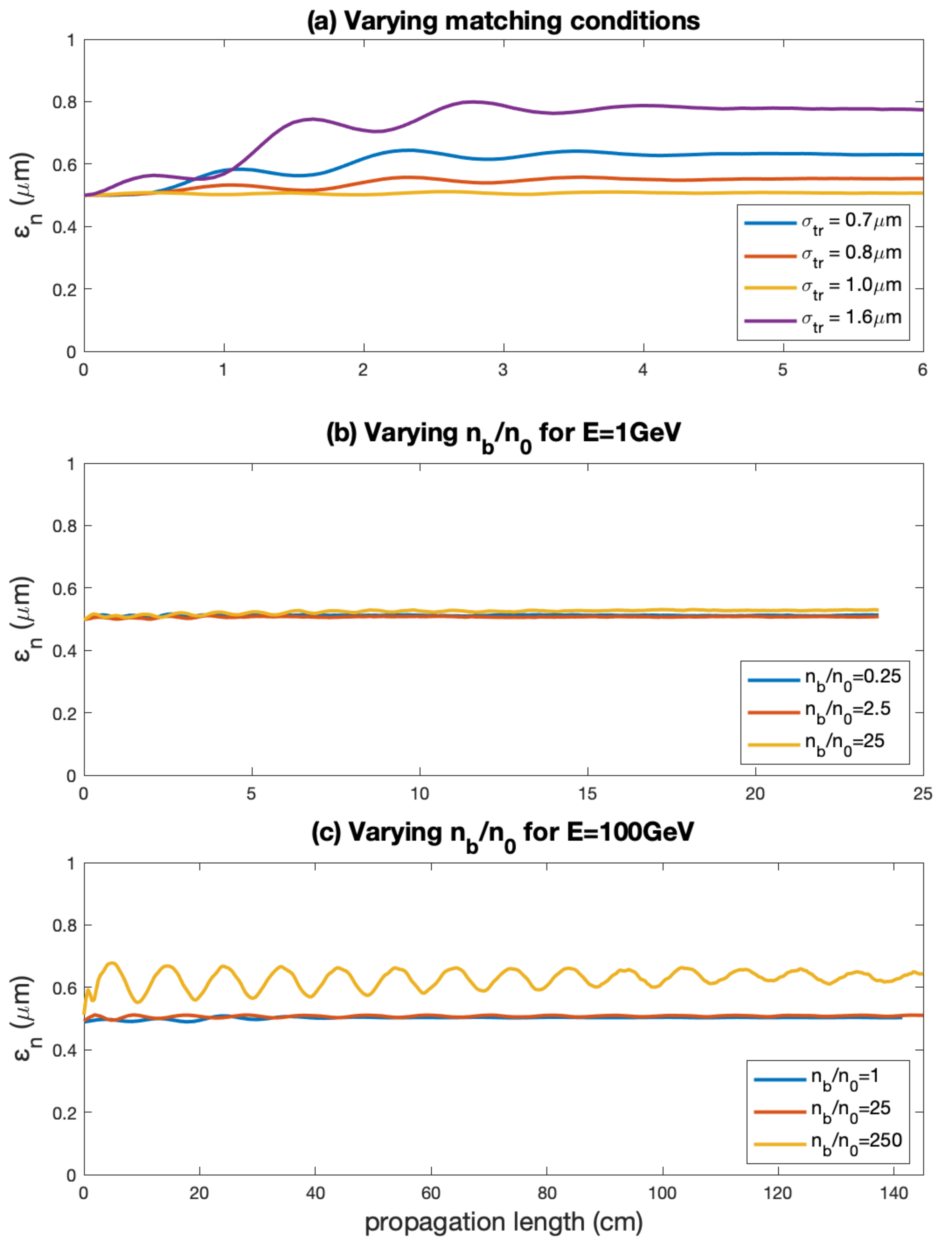
- (b): this is still valid for $n_b/n_0 \gg 1$, that is for a nonlinear positron load in a linearly-driven plasma wakefield.
- (c): for $k_b\sigma_z > 1$, the situation qualitatively changes, and new ideas are needed to mitigate emittance growth $$k_b = \frac{1}{c}\sqrt{\frac{n_b e^2}{m_e \epsilon_0}} = \sqrt{\frac{n_b}{n_0}}k_p$$



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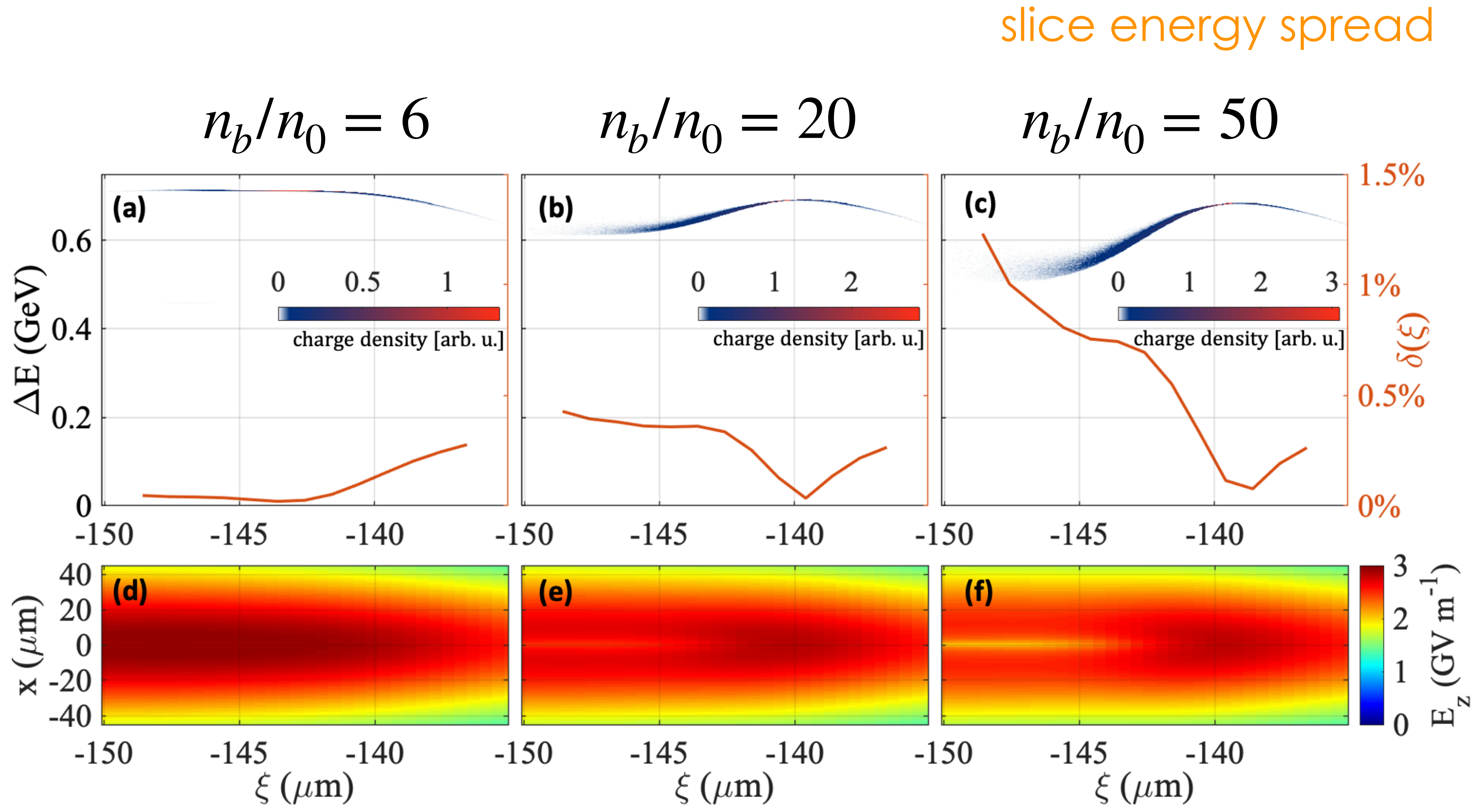
	1.01	0.5	0.41	2.14	0.25	0.045	1	0.16	1.74
Fig. 3(b)	1.00	0.5	0.40	2.14	2.5	0.14	1	1.52	2.64
	0.80	0.5	0.26	2.14	25	0.45	1	9.15	5.83
	0.327	0.5	4.28	2.14	1	0.09	100	0.07	2.73
Fig. 3(b)	0.288	0.5	3.33	2.14	25	0.45	100	1.63	3.67
	0.189	0.5	1.43	2.14	250	1.4	100	5.24	30.0

Uncorrelated energy spread in quasilinear regime

Evolution of longitudinal phase space

Two contributions to the energy spread:

- Correlated energy spread: very important but can potentially be removed by dechirping or beam loading
- Uncorrelated/slice energy spread: fundamental limit, it spoils the longitudinal emittance irreversibly



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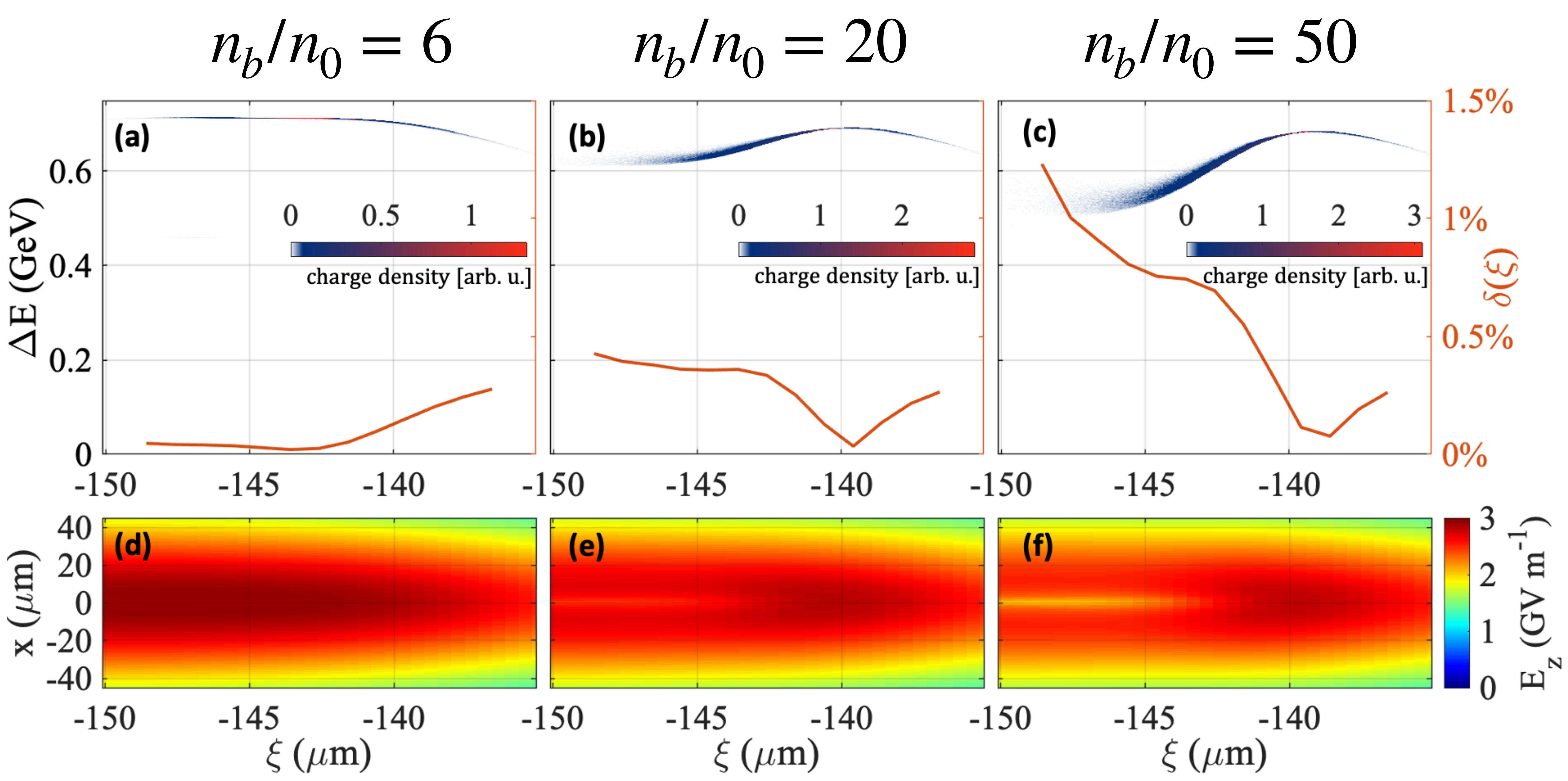
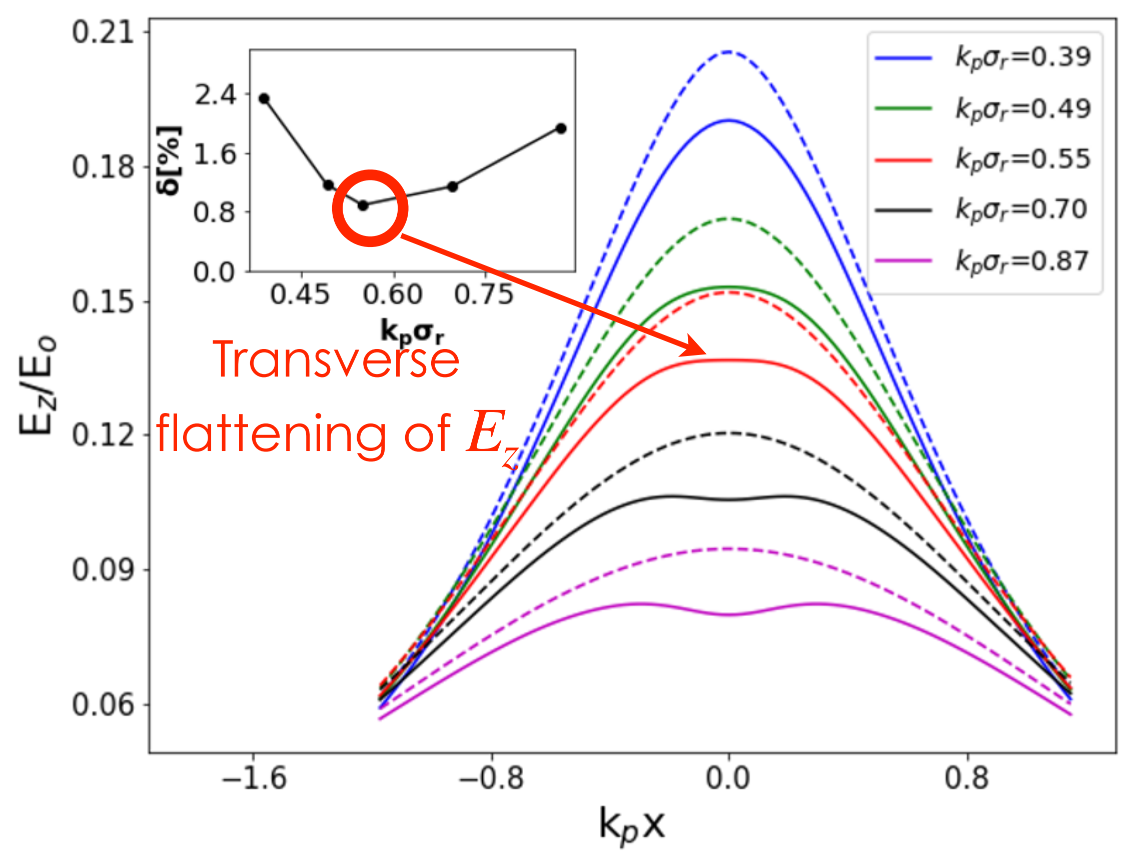
slice energy spread



Uncorrelated energy spread as figure of merit:

$$\delta = \frac{1}{\langle E_z \rangle} \left[\frac{1}{N_b} \int [E_z(x,y,\xi) - \langle E_z \rangle(\xi)]^2 n_b dx dy d\xi \right]^{1/2}$$

Driver can be optimised to minimize uncorrelated energy spread:



Energy efficiency vs beam quality tradeoff

Energy efficiency η vs uncorrelated energy spread δ

Process:

- Increasing efficiency by increasing positron load

$$\eta_{p\to t} = \left| \frac{N_t \langle E_z \rangle_t}{N_d \langle E_z \rangle_d} \right|$$

- Re-optimize drive beam size for each value of the positron load

- Determine uncorrelated energy spread δ

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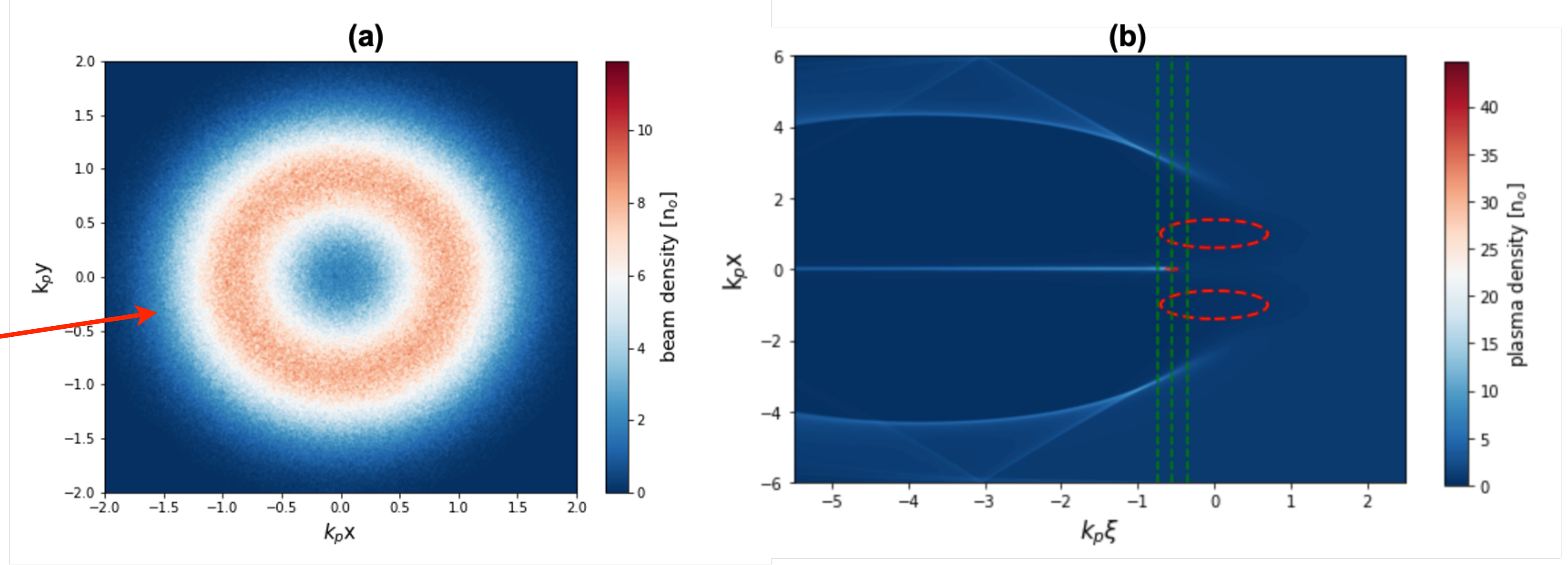
Regimes considered here with uniform plasma:

- Linearly-driven plasma wakefield, linear or nonlinear positron load
- Moderately nonlinear regime, driver with $n_b/n_0 \in [1, 2]$ and $\Lambda < 1$
- Nonlinear plasma wakefield with donut-shaped drivers



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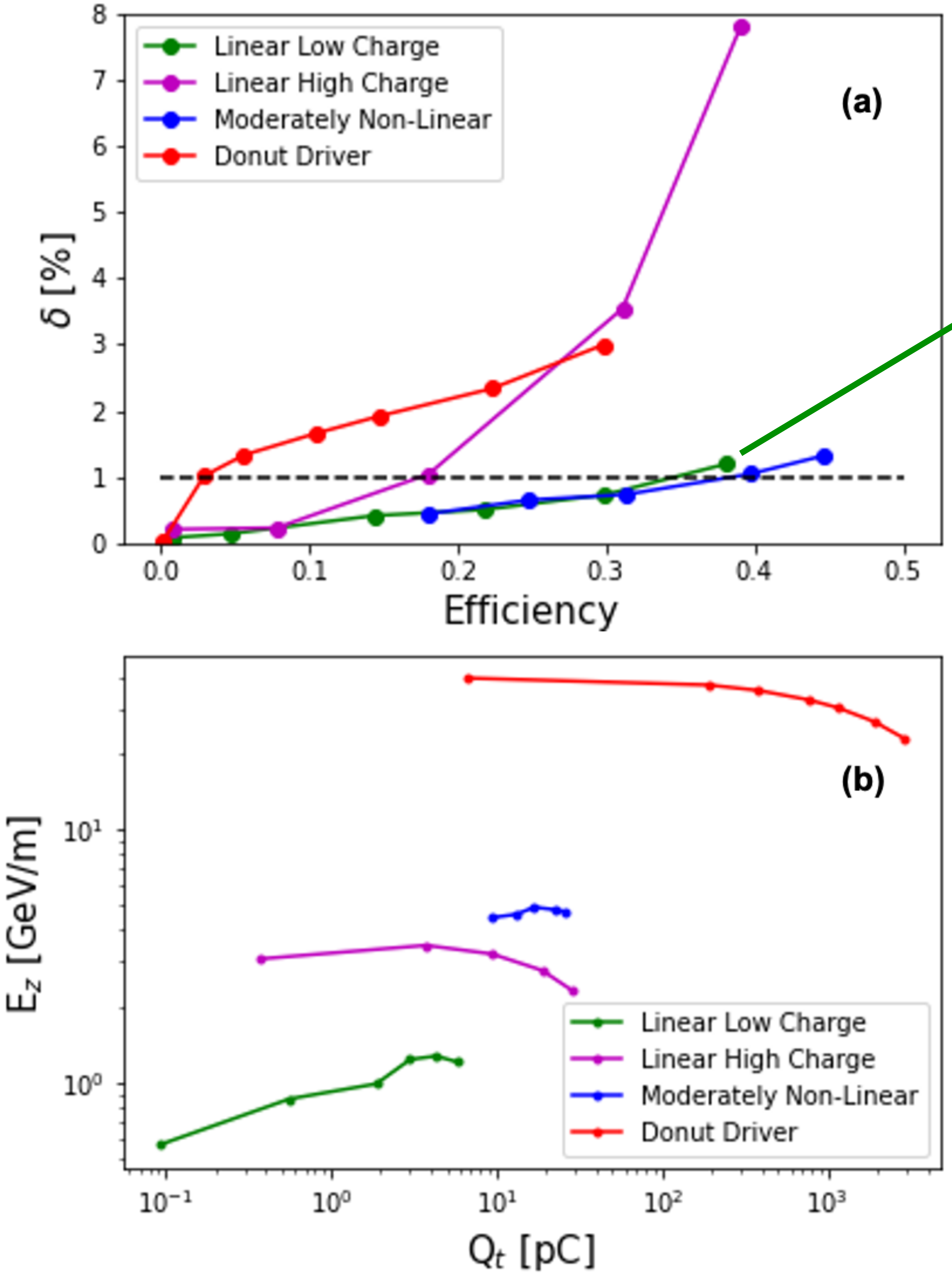
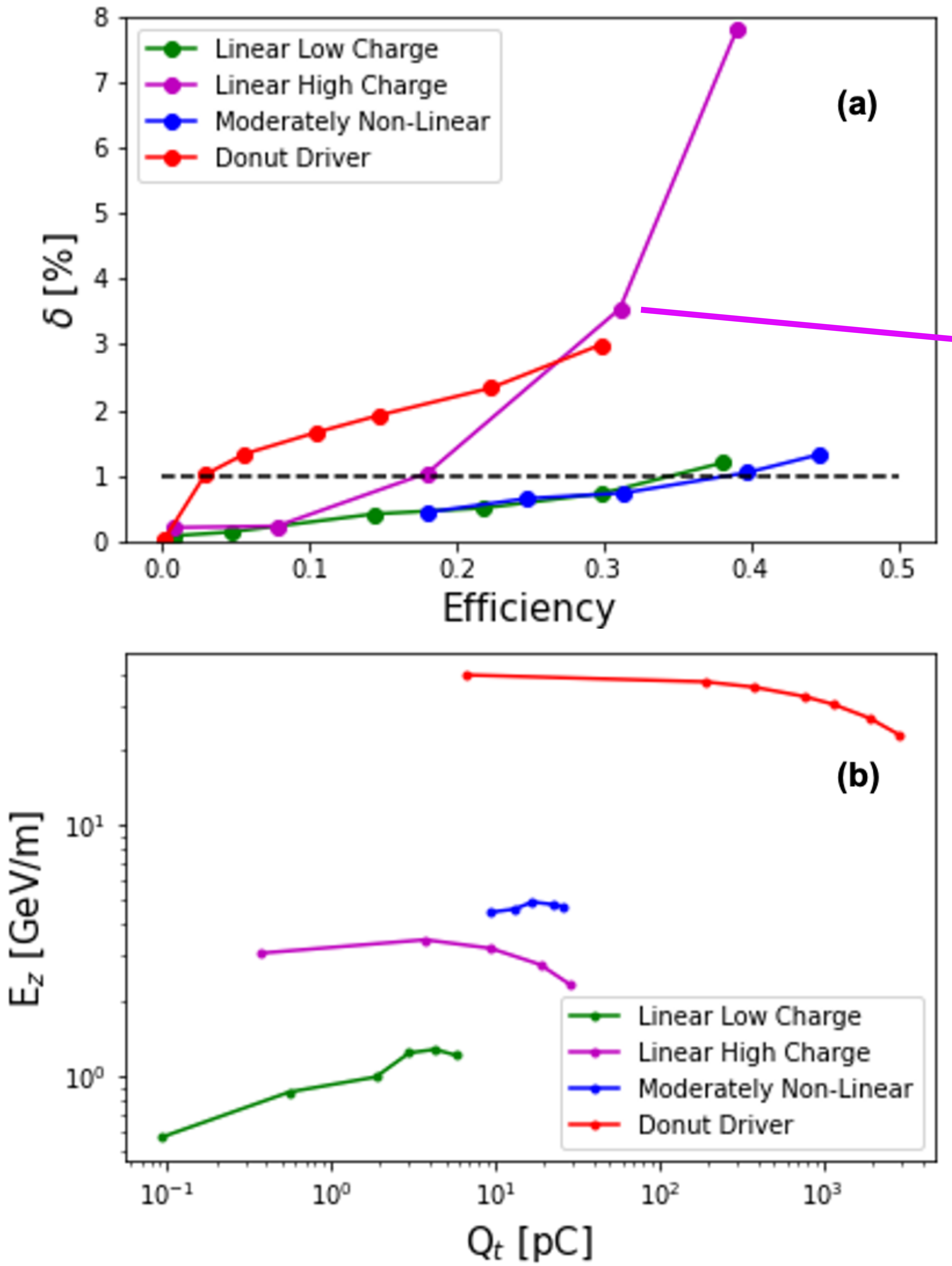


Observations:

- At low drive charge (38 pC), can reach $\eta \sim 30\,\%$ with $\delta \lesssim 1\,\%$, but positron charge is limited to 5 pC and $E_z \sim 1\ \mathrm{GV\ m^{-1}}$

	Linear low charge		Linear high charge		Moderately nonlinear		Donut driver	
	Driver	Trailing	Driver	Trailing	Driver	Trailing	Driver	Trailing
σ_r (μm)	6.09–19.27	1.19	12.19–14.56	1.19	6.28–8.22	1.19	9.4	0.85
σ_z (μm)	16.7	2.14	16.7	2.14	16.7	2.14	16.7	2.14
n_b/n_0	0.05–0.5	0.25–15.5	0.35–0.5	1–75	1.1–1.88	25–70	2.97	35–15 000
$k_p\xi$	0	−6.2	0	−6.2	0	−6.25 – −5.90	0	−0.55

Energy efficiency η vs uncorrelated energy spread δ



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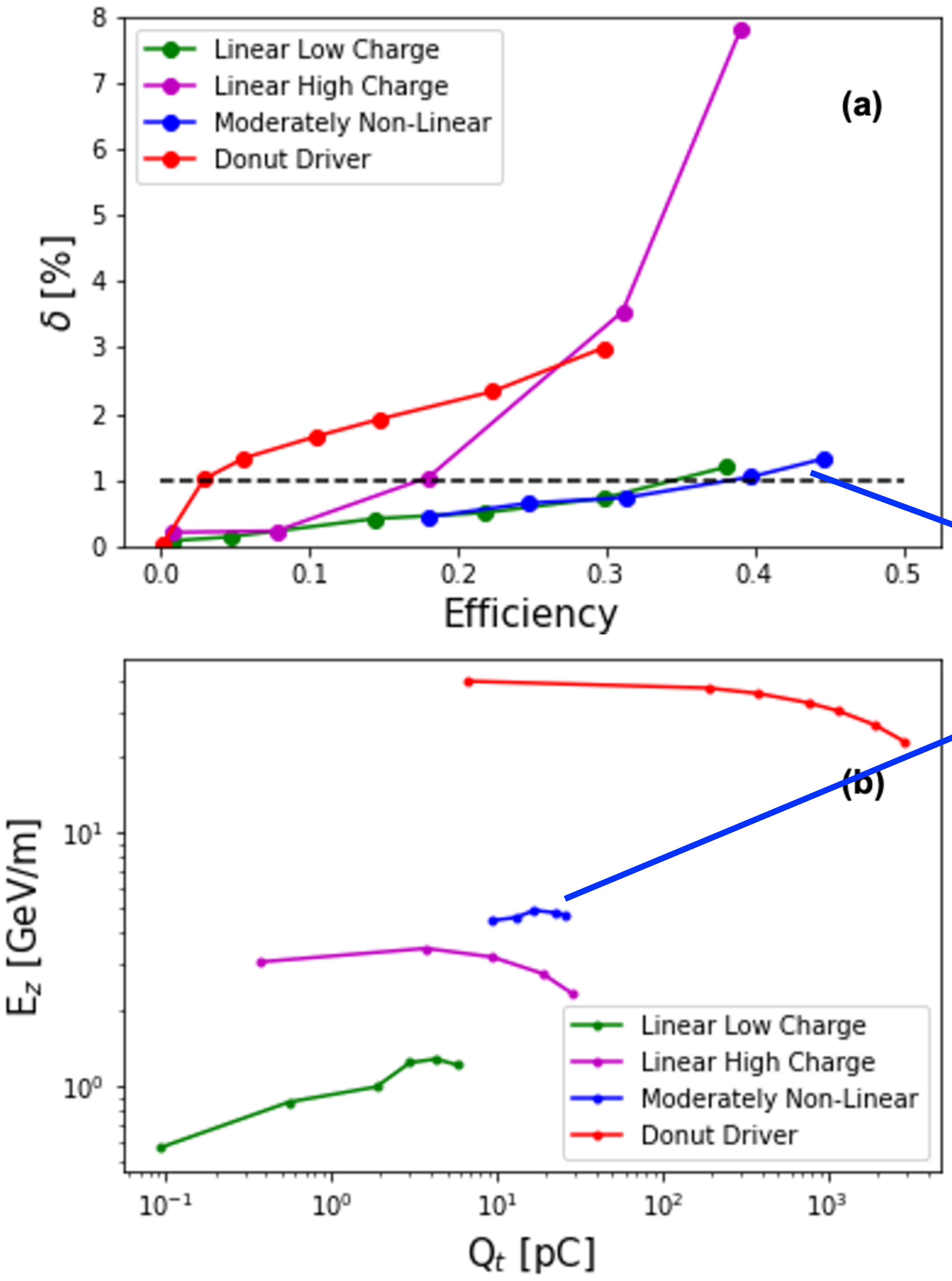

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- When continuing to optimise drive beam size at high drive charge (152 pC), one transitions to a moderately nonlinear regime. $\eta \sim 40\,\%$ with $\delta \lesssim 1\,\%$ possible with 25 pC of positron charge and $E_z \simeq 5\ \mathrm{GV\,m^{-1}}$.

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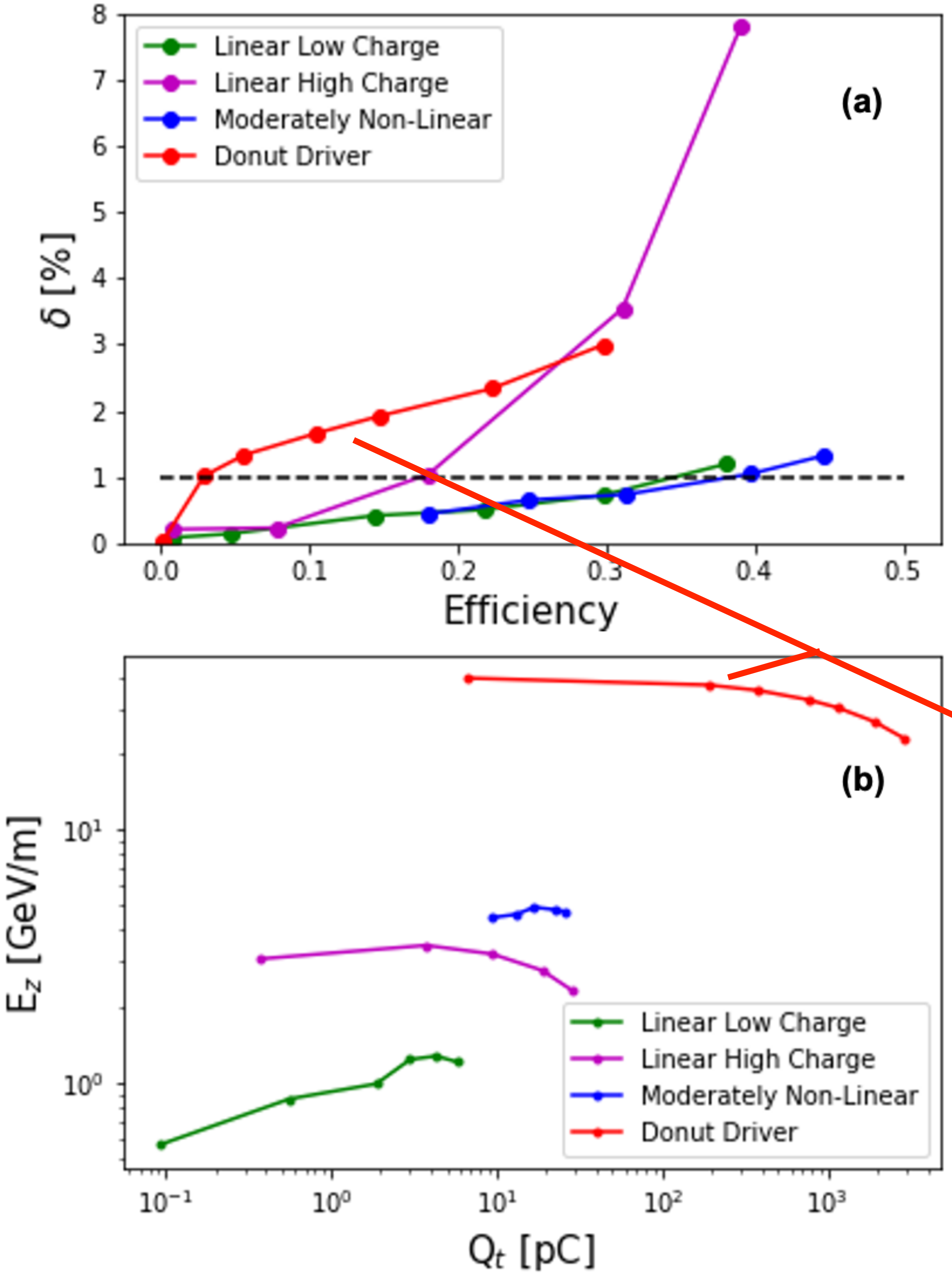
Energy efficiency η vs uncorrelated energy spread δ



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- Nonlinear donut drivers: very high fields and positron charges, but degraded tradeoff between η and δ. Limited to $\eta \lesssim 5\,\%$ for $\delta \lesssim 1\,\%$.

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The positron problem

Plasma electron motion and transverse beam loading

The positron problem

Physics > Accelerator Physics

arXiv:2309.10495v1 (physics)

[Submitted on 19 Sep 2023]

Positron Acceleration in Plasma Wakefields

G.J.Cao, C.A.Lindstrøm, E.Adli, S.Corde, S.Gessner

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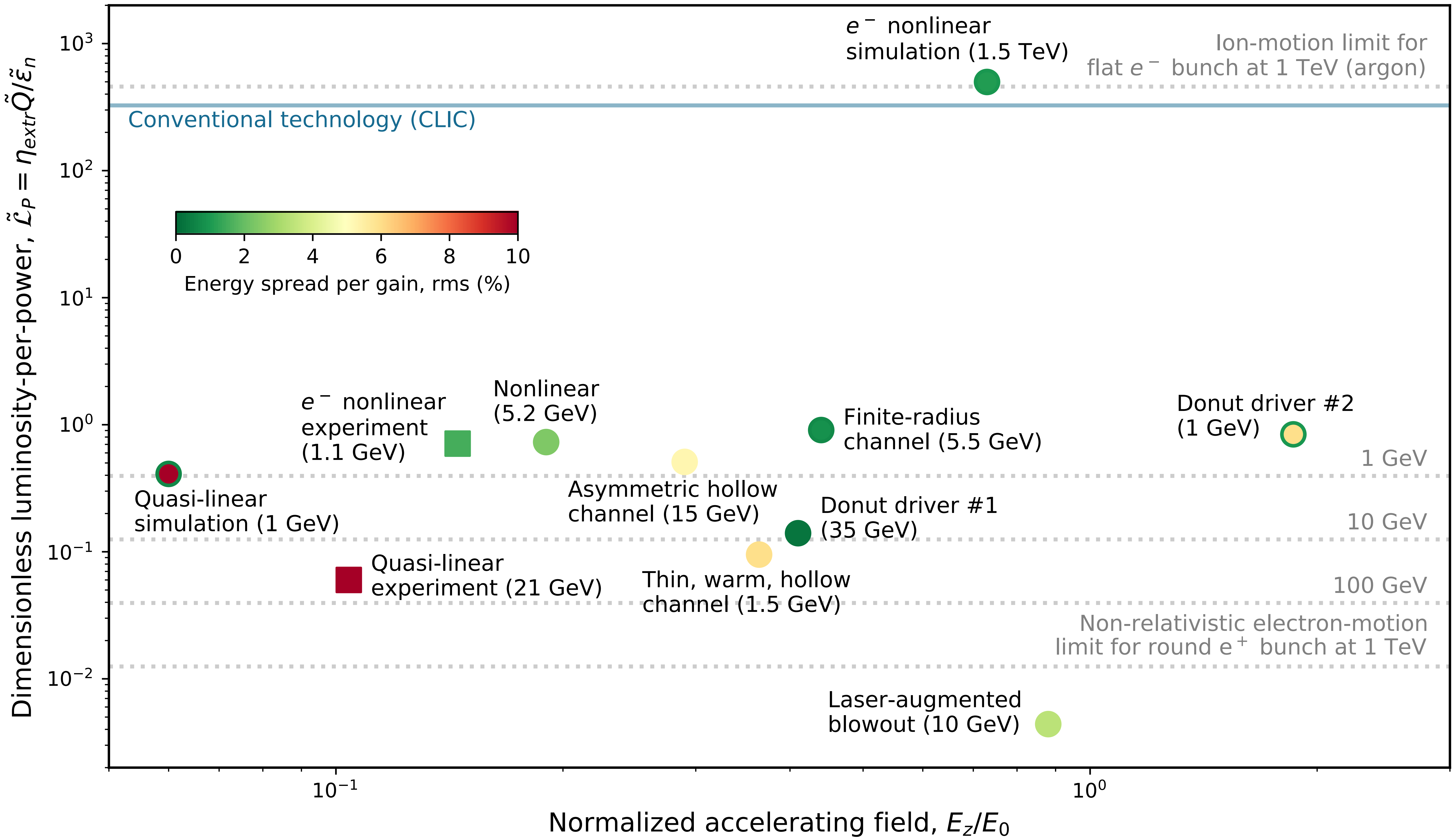
Plasma acceleration has emerged as a promising technology for future particle accelerators, particularly linear colliders. Significant progress has been made in recent decades toward high-efficiency and high-quality acceleration of electrons in plasmas. However, this progress does not generalize to acceleration of positrons, as plasmas are inherently charge asymmetric. Here, we present a comprehensive review of historical and current efforts to accelerate positrons using plasma wakefields. Proposed schemes that aim to increase the energy efficiency and beam quality are summarised and quantitatively compared. A dimensionless metric that scales with the luminosity-per-beam power is introduced, indicating that positron-acceleration schemes are currently below the ultimate requirement for colliders. The primary issue is electron motion; the high mobility of plasma electrons compared to plasma ions, which leads to non-uniform accelerating and focusing fields that degrade the beam quality of the positron bunch, particularly for high efficiency acceleration. Finally, we discuss possible mitigation strategies and directions for future research.



Cao, Lindstrøm et al., arXiv:2309.10495 (2023)

The positron problem

Figure of merit:
luminosity per power

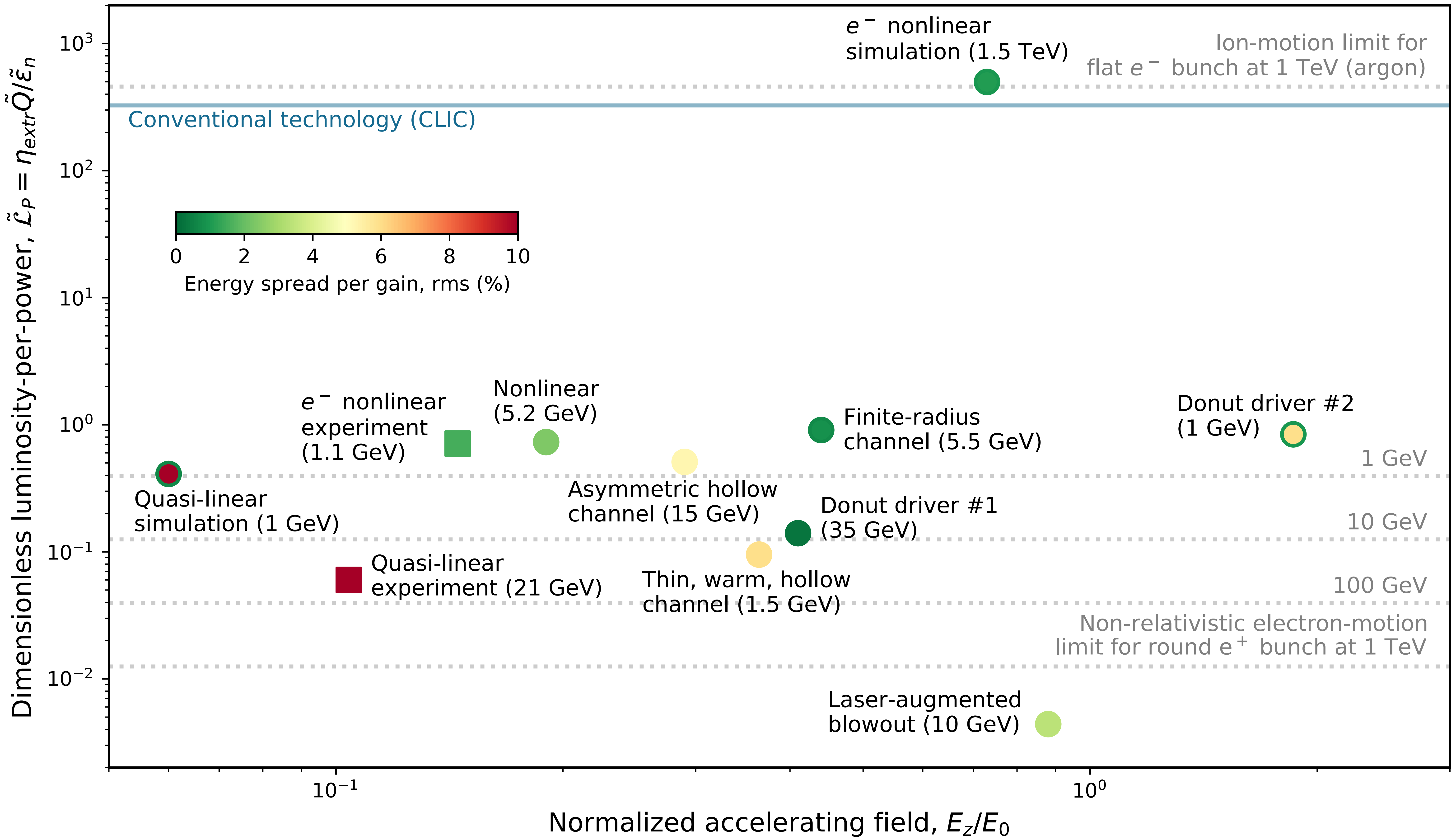
$$\mathscr{L} \approx \frac{1}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \epsilon_{nx}}} \frac{\eta N}{\sqrt{\beta_y \epsilon_{ny}}}$$

$$\frac{\mathscr{L}}{P_{\text{wall}}} \propto \tilde{\mathscr{L}}_P = \frac{\eta_{\text{extr}} \tilde{Q}}{\tilde{\epsilon}_n}$$

with:

$$\tilde{\epsilon}_n = k_p \sqrt{\epsilon_{nx} \epsilon_{ny}}$$

$$\tilde{Q} = 4\pi r_e k_p N$$



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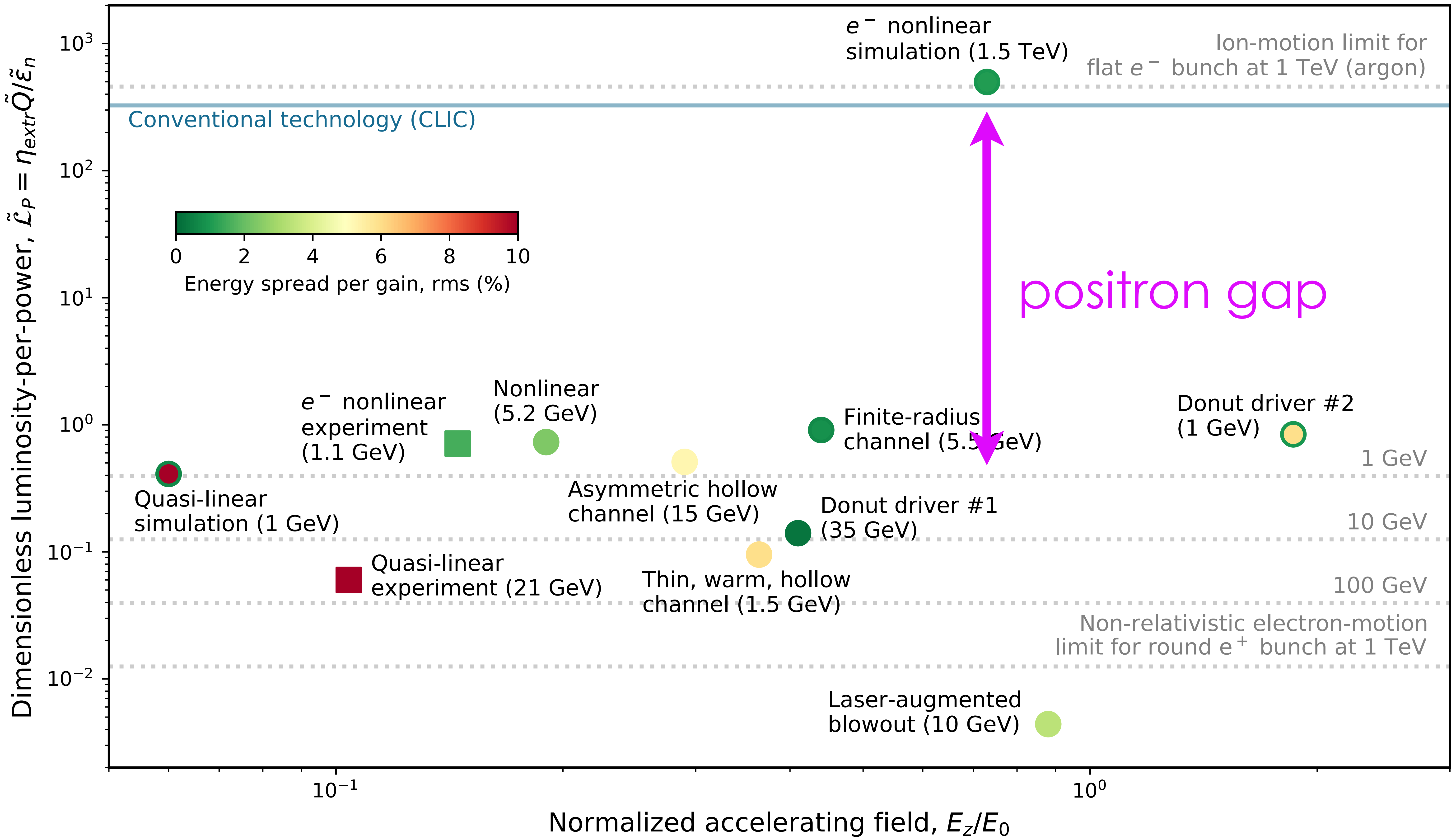
The positron problem

Why such a big gap?



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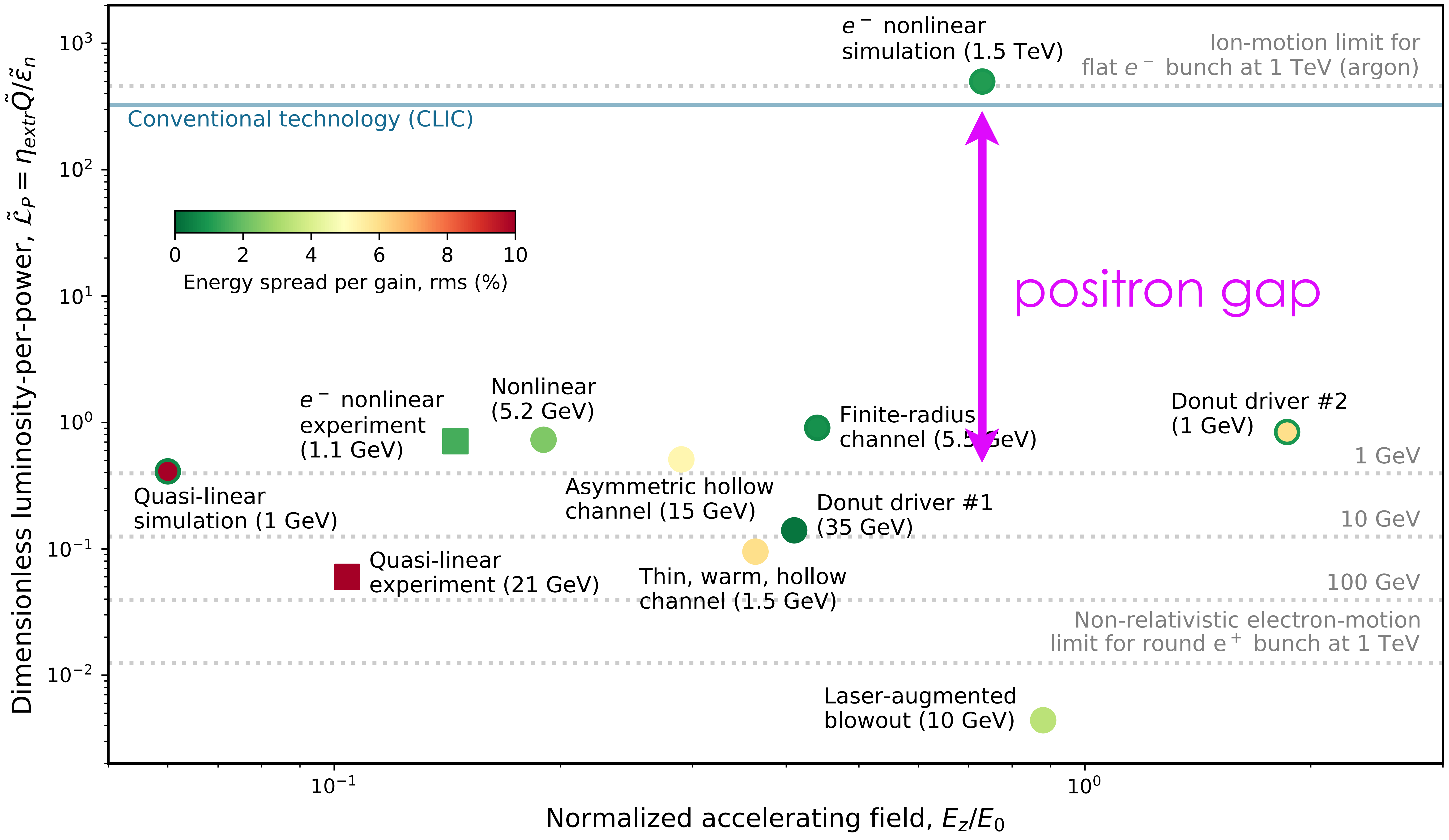
The positron problem

Why such a big gap?

- Plasma electrons used for positron focusing are very light, much lighter than ions used for electron focusing in blowout:

$$m_e \ll m_i$$



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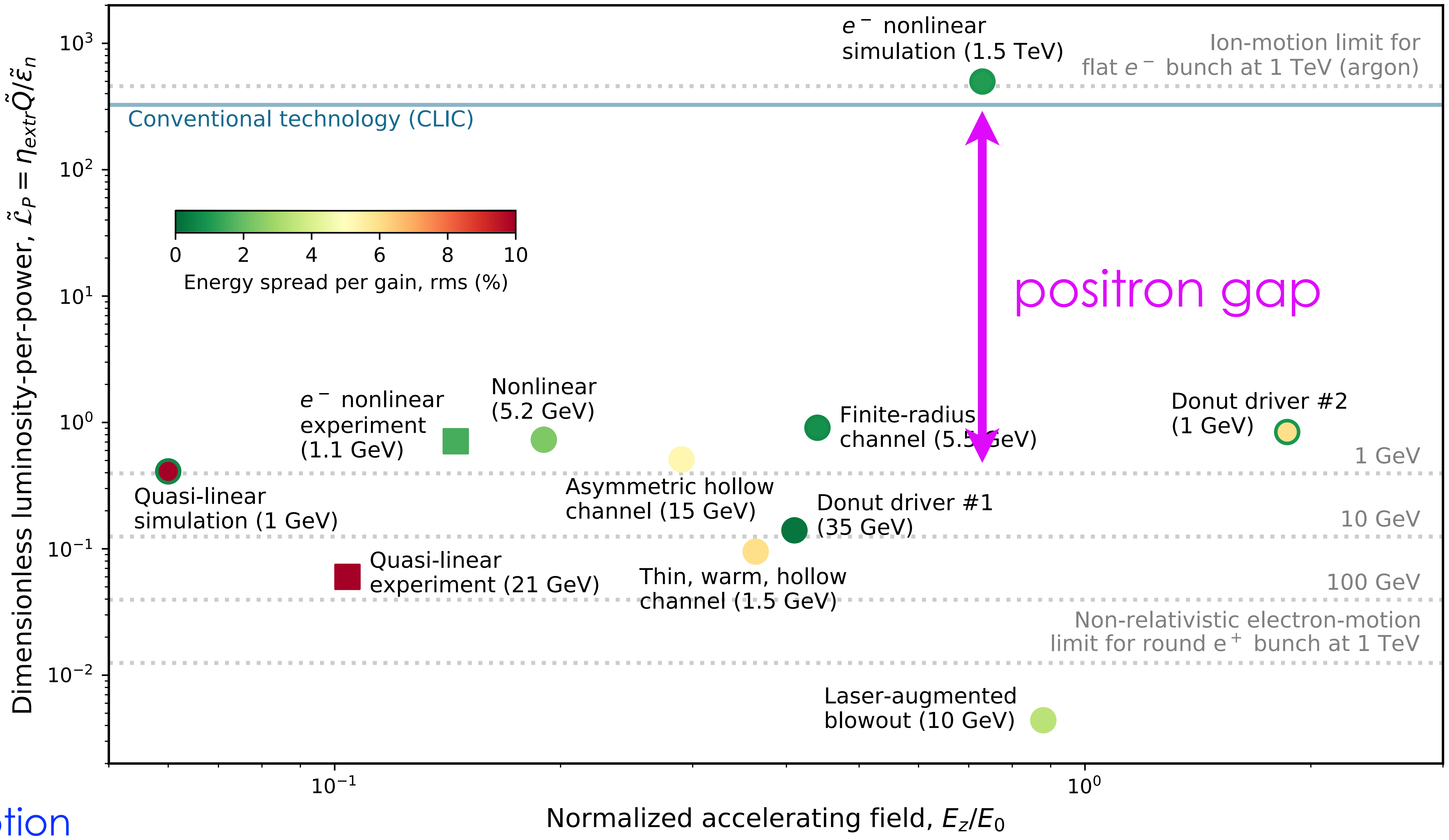
- Plasma electron motion similar to ion motion in blowout, and can be described by a phase advance in the bunch:

$$\Delta\phi_i \simeq k_i \Delta\zeta = \sqrt{\frac{\mu_0 e^2}{2} \frac{Z\sigma_z N}{m_i} \sqrt{\frac{r_e \gamma n_0}{\epsilon_{nx}\epsilon_{ny}}}}$$ ion motion

$$\Delta\phi_e \simeq k_e \Delta\zeta = \sqrt{\frac{\mu_0 e^2}{2} \frac{\sigma_z N}{\gamma_{pe} m_e} \sqrt{\frac{r_e \gamma \Delta n}{\epsilon_{nx}\epsilon_{ny}}}}$$ electron motion



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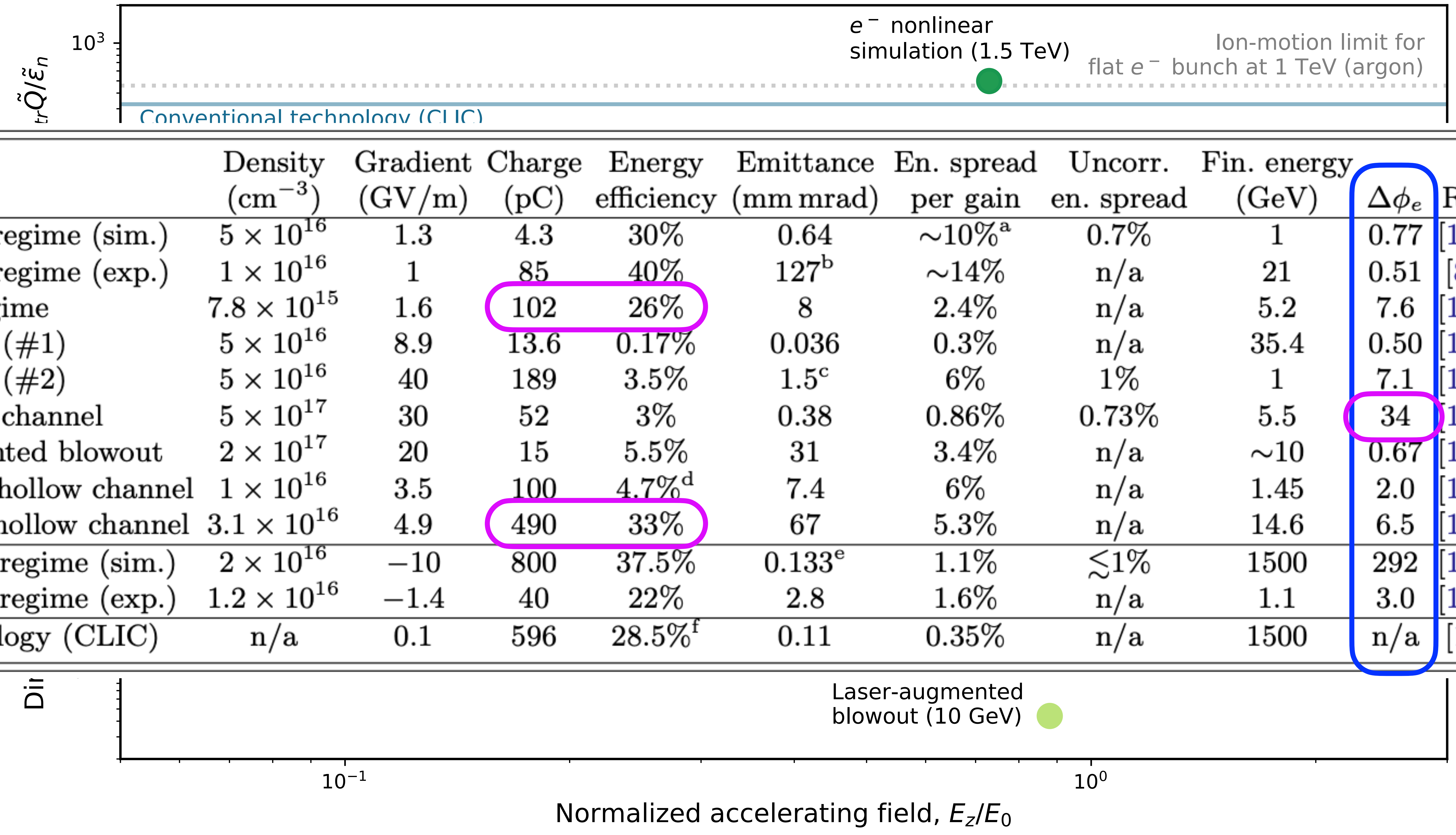
The positron problem

What can we learn about plethora of schemes?

- Regimes overcoming $\Delta\phi_e \lesssim \pi/2$ limit are the most promising.
- Charge also very important, favouring nonlinear regimes.



Scheme	Density (cm^{-3})	Gradient (GV/m)	Charge (pC)	Energy efficiency	Emittance (mm mrad)	En. spread per gain	Uncorr. en. spread	Fin. energy (GeV)	$\Delta\phi_e$	Ref.
Quasi-linear regime (sim.)	5×10^{16}	1.3	4.3	30%	0.64	~10% [a]	0.7%	1	0.77	[146]
Quasi-linear regime (exp.)	1×10^{16}	1	85	40%	127 [b]	~14%	n/a	21	0.51	[81]
Nonlinear regime	7.8×10^{15}	1.6	102	26%	8	2.4%	n/a	5.2	7.6	[154]
Donut driver (#1)	5×10^{16}	8.9	13.6	0.17%	0.036	0.3%	n/a	35.4	0.50	[159]
Donut driver (#2)	5×10^{16}	40	189	3.5%	1.5 [c]	6%	1%	1	7.1	[146]
Finite-radius channel	5×10^{17}	30	52	3%	0.38	0.86%	0.73%	5.5	34	[171]
Laser-augmented blowout	2×10^{17}	20	15	5.5%	31	3.4%	n/a	~10	0.67	[178]
Thin, warm, hollow channel	1×10^{16}	3.5	100	4.7% [d]	7.4	6%	n/a	1.45	2.0	[179]
Asymmetric hollow channel	3.1×10^{16}	4.9	490	33%	67	5.3%	n/a	14.6	6.5	[180]
e^- nonlinear regime (sim.)	2×10^{16}	−10	800	37.5%	0.133 [e]	1.1%	≲1%	1500	292	[182]
e^- nonlinear regime (exp.)	1.2×10^{16}	−1.4	40	22%	2.8	1.6%	n/a	1.1	3.0	[183]
Conv. technology (CLIC)	n/a	0.1	596	28.5% [f]	0.11	0.35%	n/a	1500	n/a	[10]

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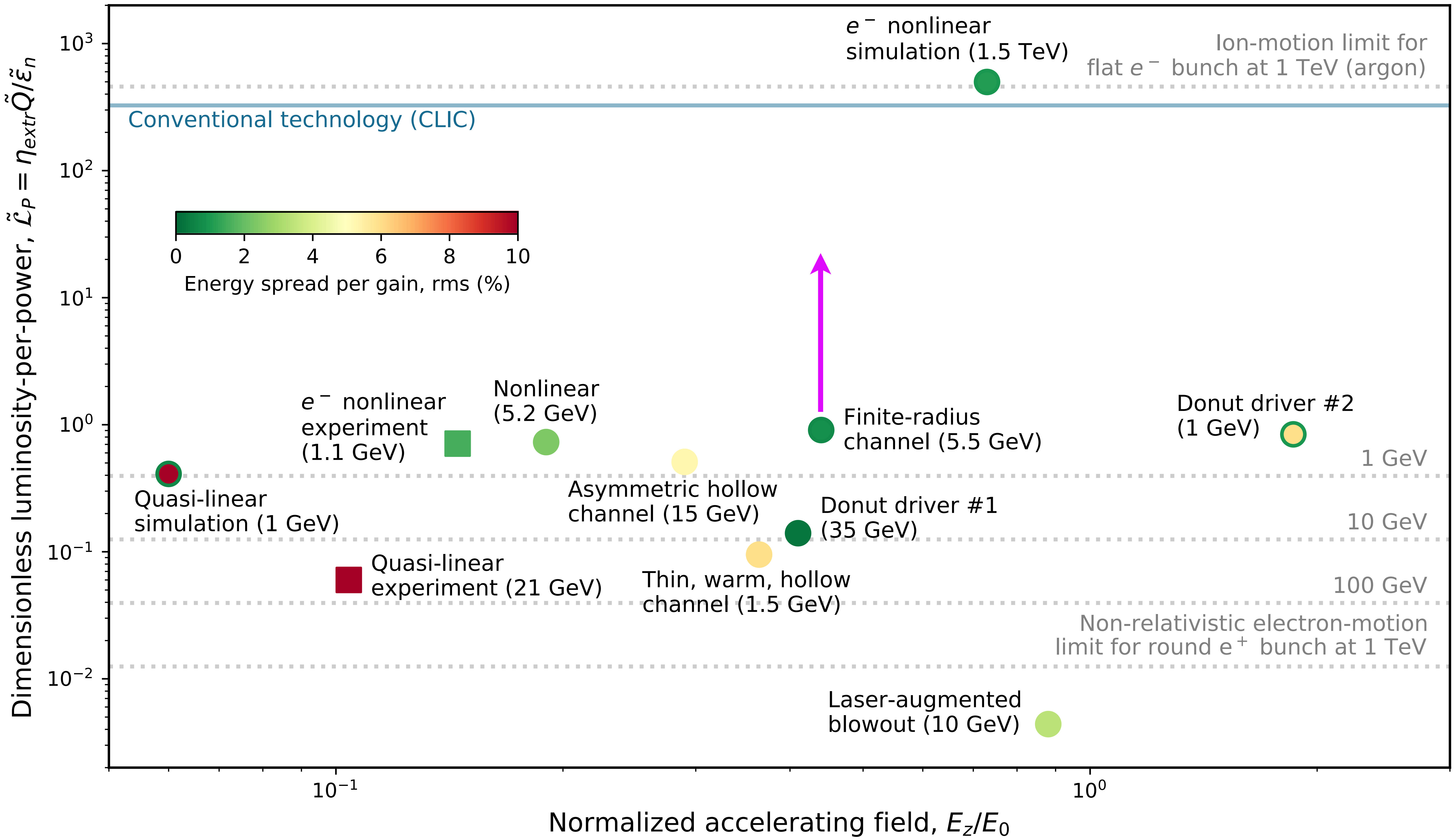
The positron problem

Strategies to fill the gap:

$\Delta\phi_e$

- Slice-by-slice matching
- Plasma electron temperature
- Spread plasma electrons: different plasma electrons to focus different positron beam slices



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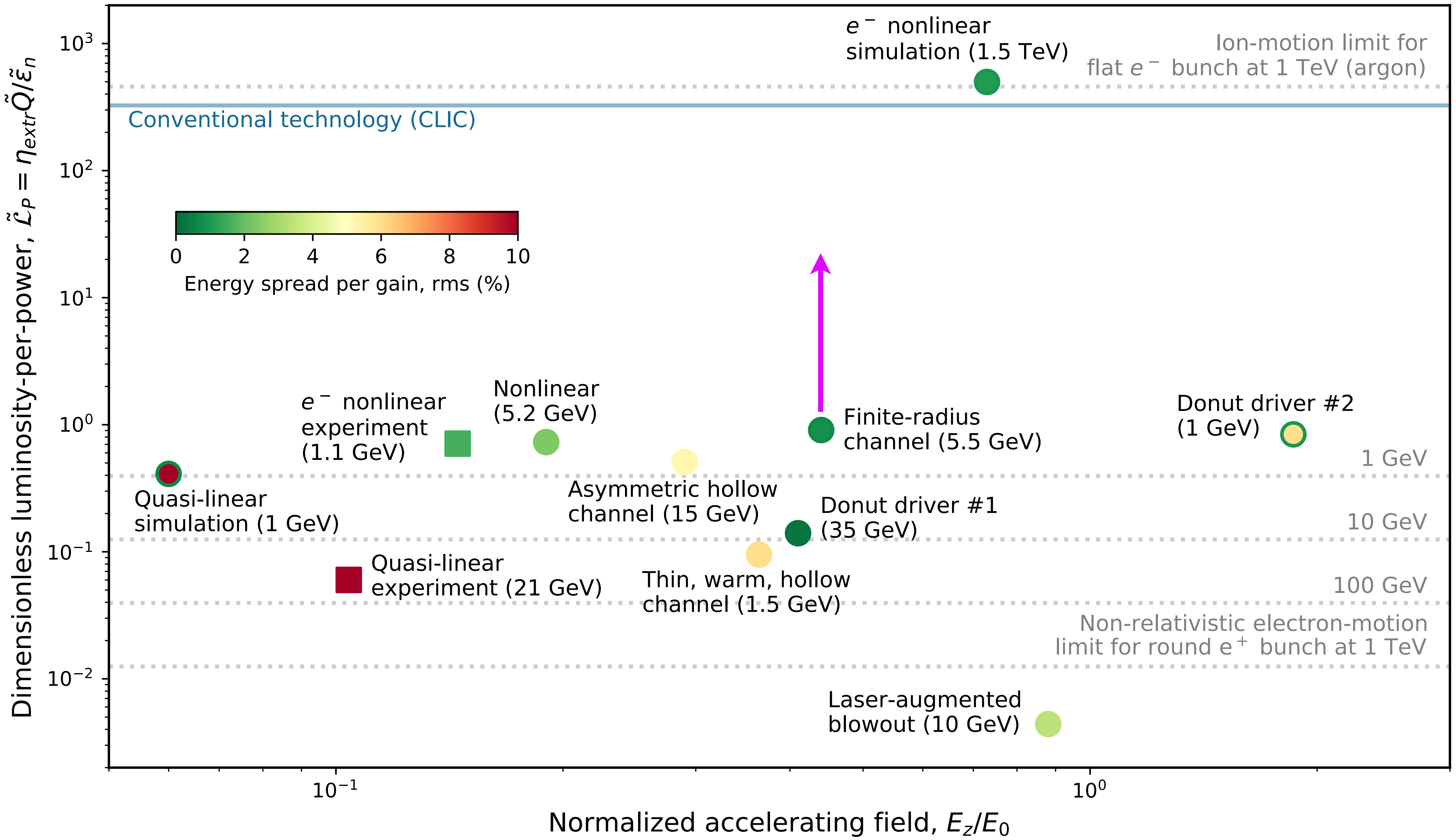
- Energy recovery to improve efficiency (next talk from S. Gessner)
- Decrease emittance to compensate for low efficiency in $\tilde{\mathscr{L}}_P$



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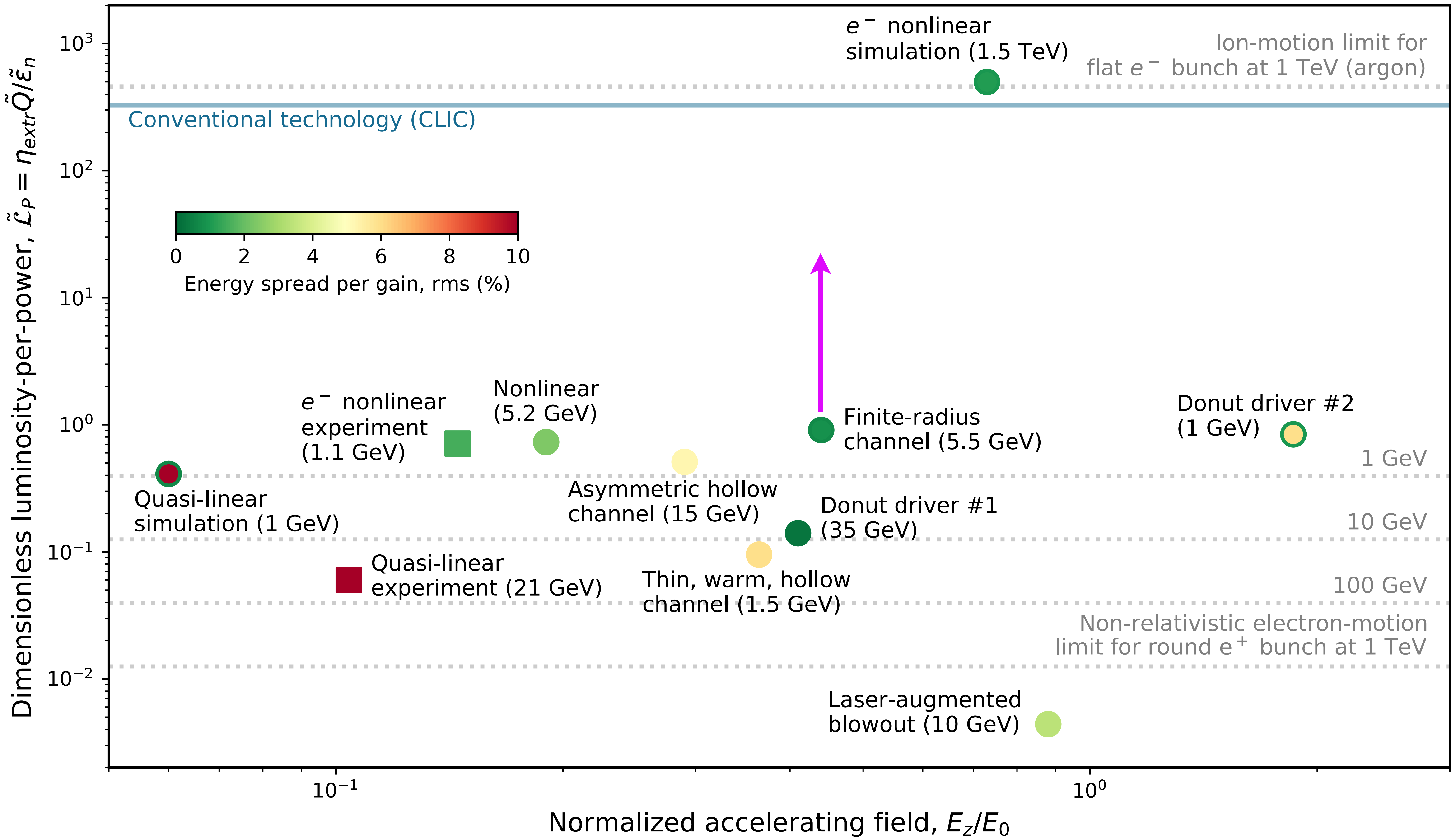
- Low focusing and large beta function
- High Lorentz factor for plasma electrons



Cao, Lindstrøm et al., arXiv:2309.10495 (2023)

Conclusion

- Energy efficiency comes with a strong positron load, and thus with transverse beam loading

- For most regimes, there is a tradeoff between energy efficiency and beam quality (e.g. emittance, uncorrelated energy spread)

- Luminosity-per-power scaling and electron motion highlights future directions

Thank you for your attention