Positron acceleration in plasma wakefields for linear colliders: a review of progress and challenges

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 034801 (2024)

Review Article

Positron acceleration in plasma wakefields

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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
  - ➢ Not directly suited for positrons
- Preliminary considerations with positron-loaded quasilinear plasma wakefields
  - ➢ Efficiency
  - ➢ Evolution of transverse emittance
  - ➢ Uncorrelated energy spread
- Energy efficiency vs beam quality tradeoff
- The positron problem
  - ➢ Luminosity-per-power
  - ➢ Electron motion
  - ➢ Strategies

Not covered:
Truly hollow plasma acceleration
BBU instability still to be solved

Lindstrom et al., PRL 120, 124802 (2018)

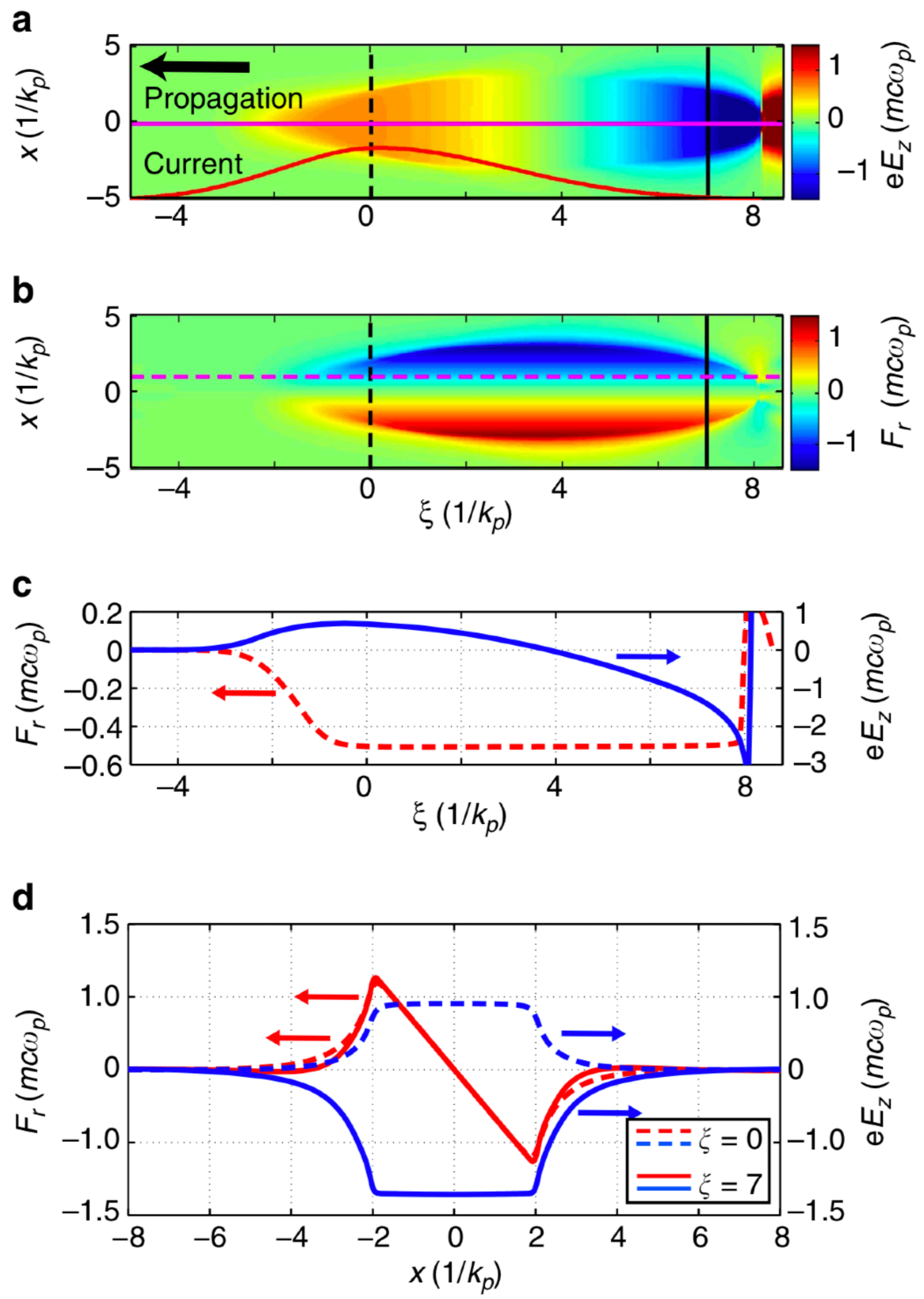
General remark: the discussion today will focus on PWFA, but is fully relevant to LWFA as well.

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.

But:

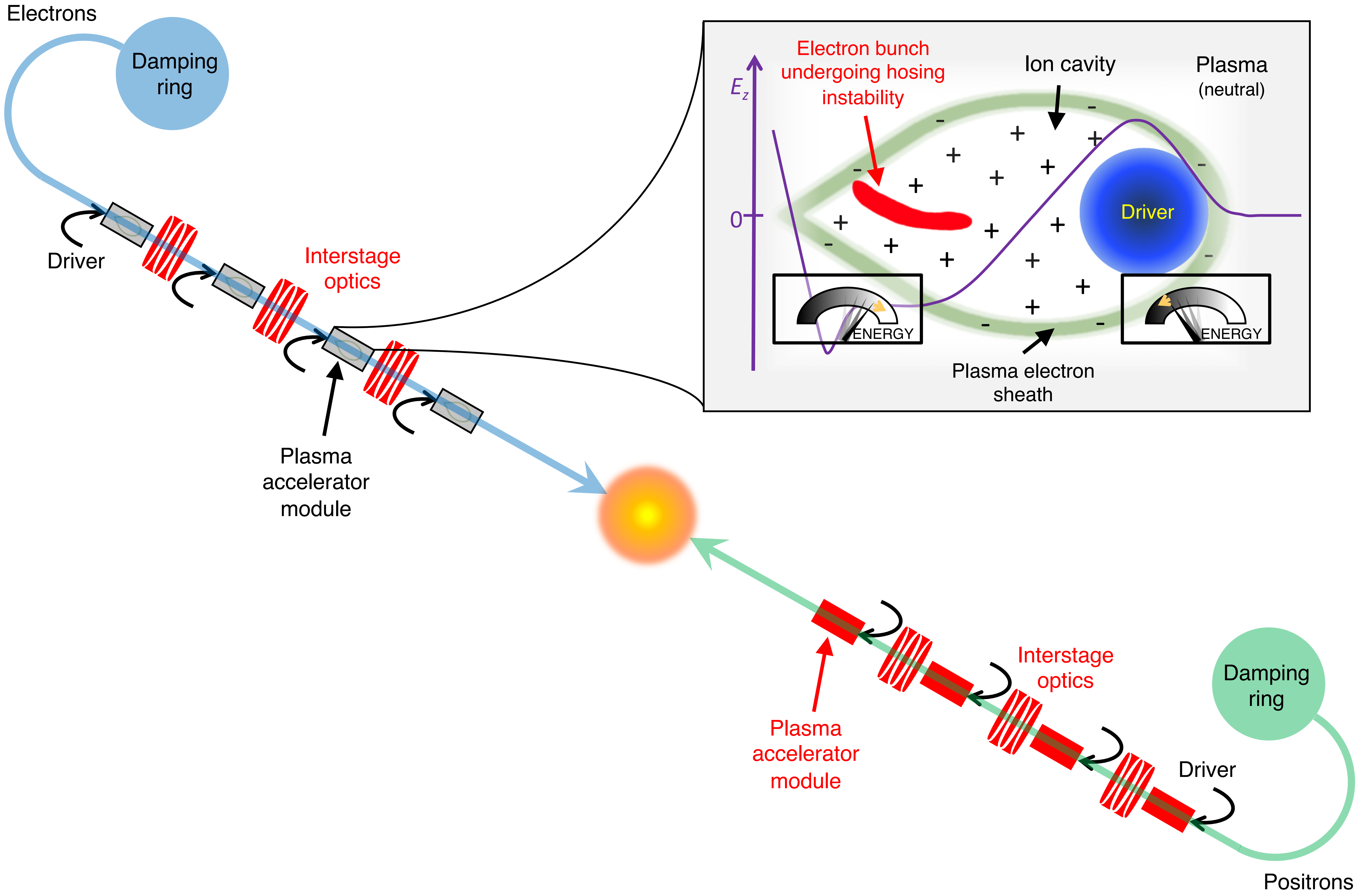
→ hosing instability may be an important limitation for collider beam parameters.

→ ion motion may lead to emittance growth.

→ what abut e^+?

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

Scientific context: challenges



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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^+?

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

Scientific context: challenges

Accelerating positrons in plasma?

Linear plasma wakefields: symmetrical for e^-/e^+. Directly applicable to linear colliders?

Nonlinear plasma wakefields: NOT symmetrical for e^-/e^+. Blowout properties for e^- not achievable for e^+.

- mobile plasma electrons
- mostly immobile plasma ions

$$m_i \gg m_e$$

Wealth of advanced regimes varying beam and plasma geometries

- common ingredient: mobile plasma electrons flowing through the e^+ bunch → physics beyond idealised blowout

Scientific context: challenges

What is the positron problem today?

Unloaded plasma wakefield suitable for e^+ acceleration (accelerating&focusing)?

NO

Loaded plasma wakefield with efficiency, beam quality, and ultimately competitive luminosity-per-power for e^+ arm?

YES

With loading comes plasma electron motion, basically ion motion with a much smaller mass

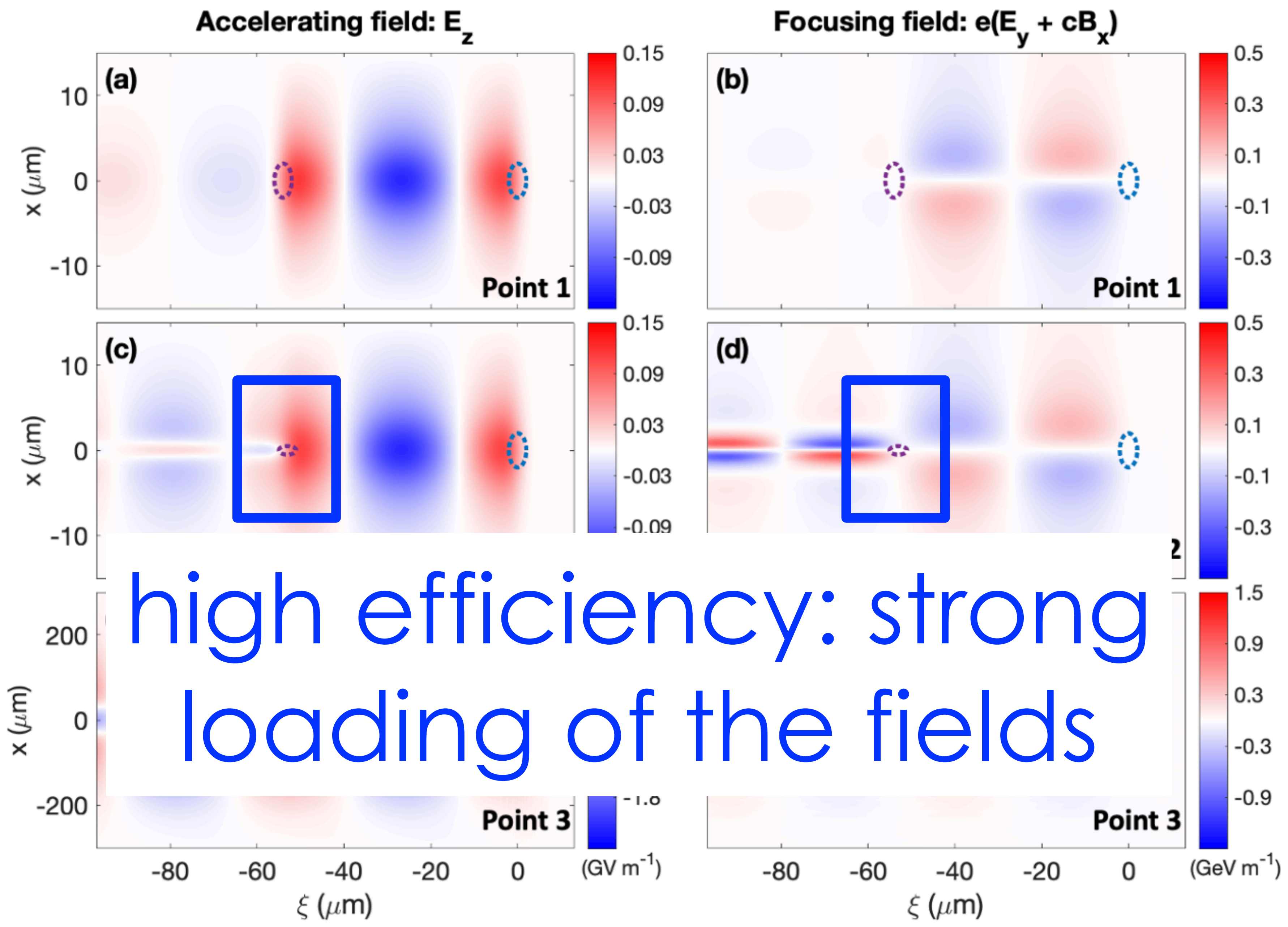
Preliminary considerations with e^+ loaded quasilinear plasma wakefields

Efficiency in quasilinear regime

Energy efficiency from plasma to accelerated trailing bunch

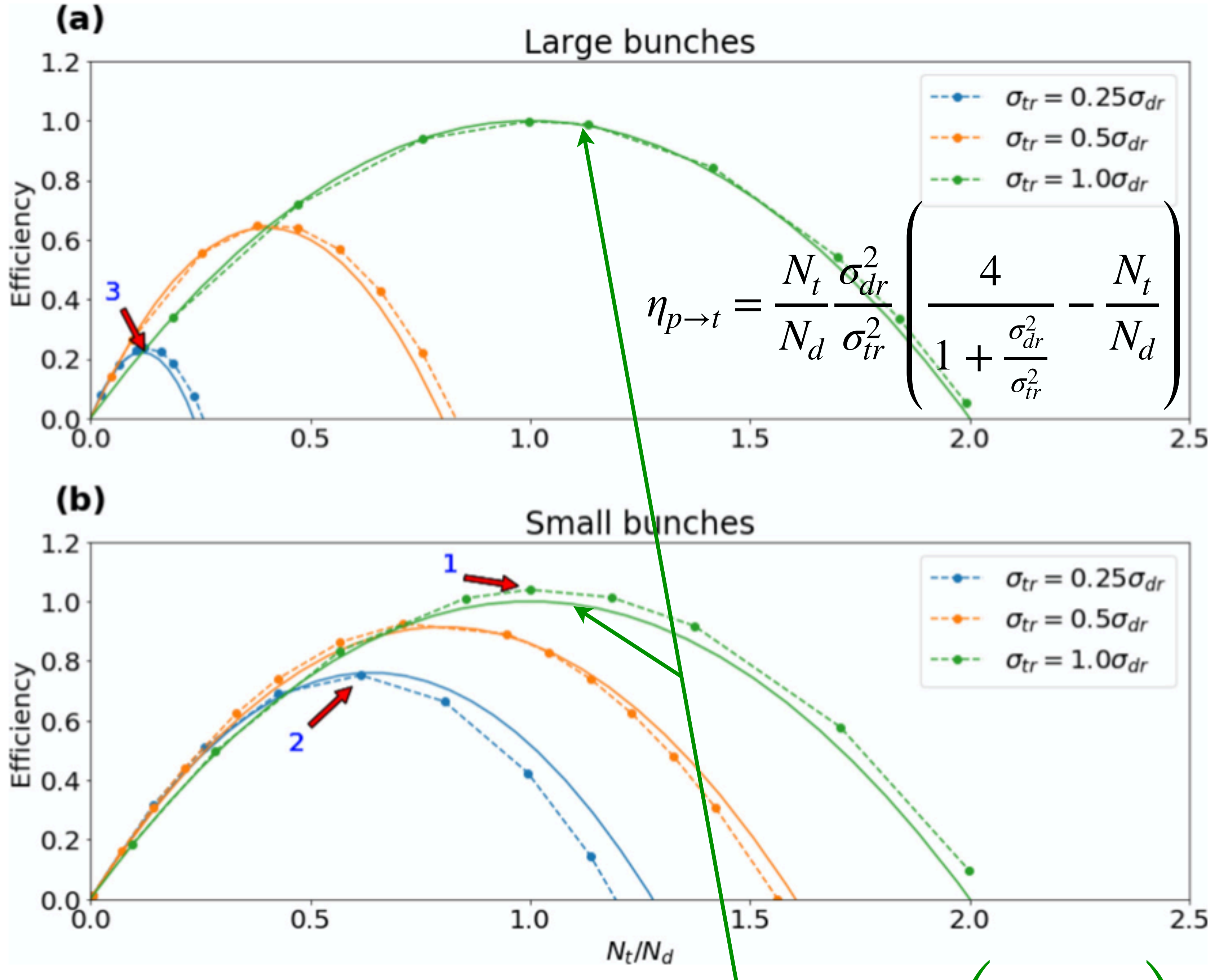
$$\eta_{p\to t} = \frac{W_{\text{gain}}}{W_{\text{loss}}} = \left|\frac{N_t\langle E_z\rangle_t}{N_d\langle E_z\rangle_d}\right| \quad \xrightarrow{\text{short bunches, linear and 1D}} \quad \eta_{p\to t,\text{1D linear}} = \frac{N_t}{N_d}\left(2-\frac{N_t}{N_d}\right)$$

Linear 3D case:



high efficiency: strong loading of the fields

- 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



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

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

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

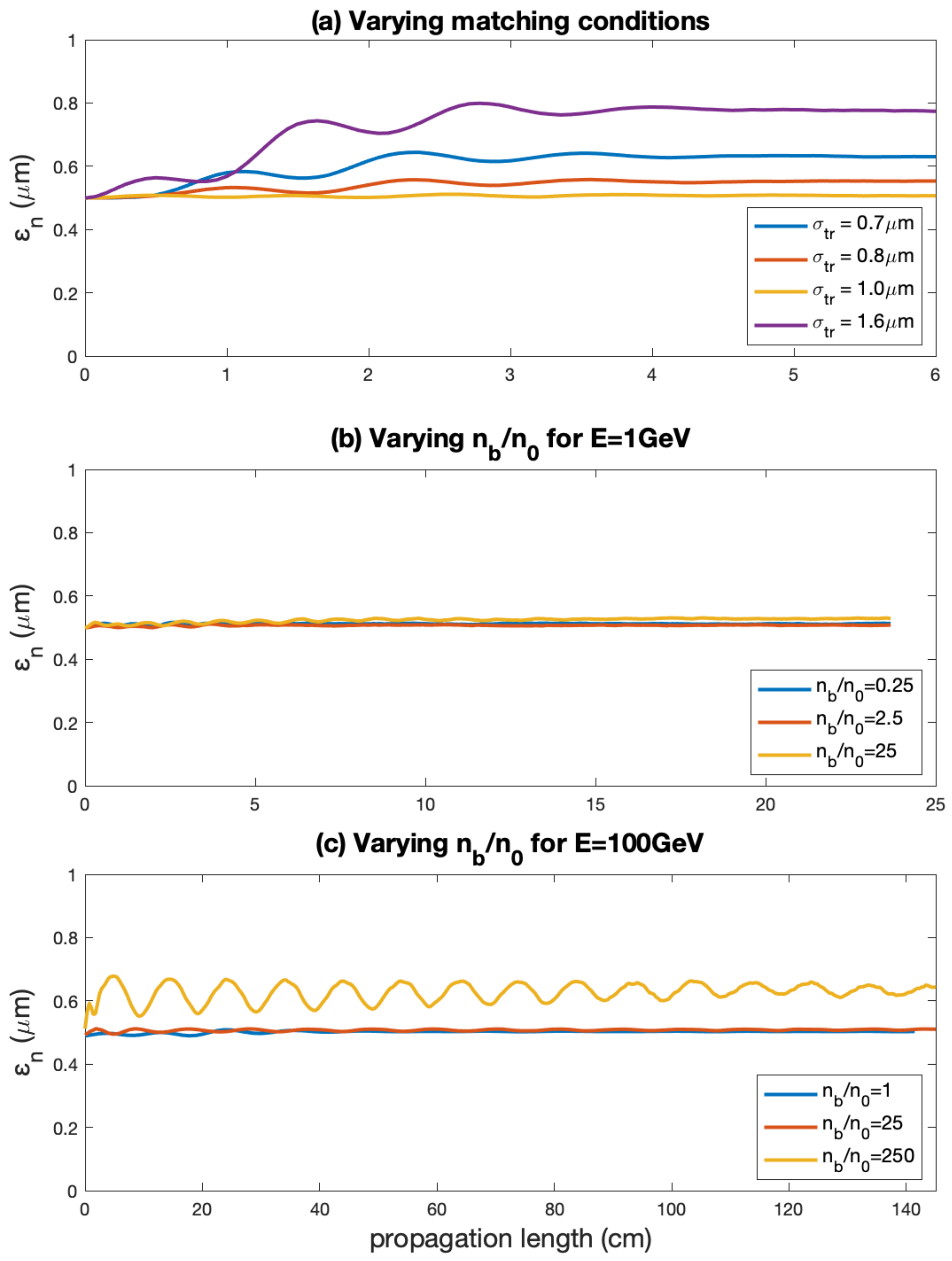
$$\Longrightarrow \beta_{\text{matched}} = 1/k_\beta$$

- (a): quasi-matching is extremely important to minimize emittance growth at acceptable levels. Demonstrate that near transverse equilibrium is possible with Gaussian positron beams.
- (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.

electron motion

- (c): for $k_b\sigma_z > 1$, the situation qualitatively changes, and new ideas are needed to mitigate emittance growth

$$k_b = \frac{1}{c}\sqrt{\frac{n_b e^2}{m_e \epsilon_0}} = \sqrt{\frac{n_b}{n_0}}k_p$$

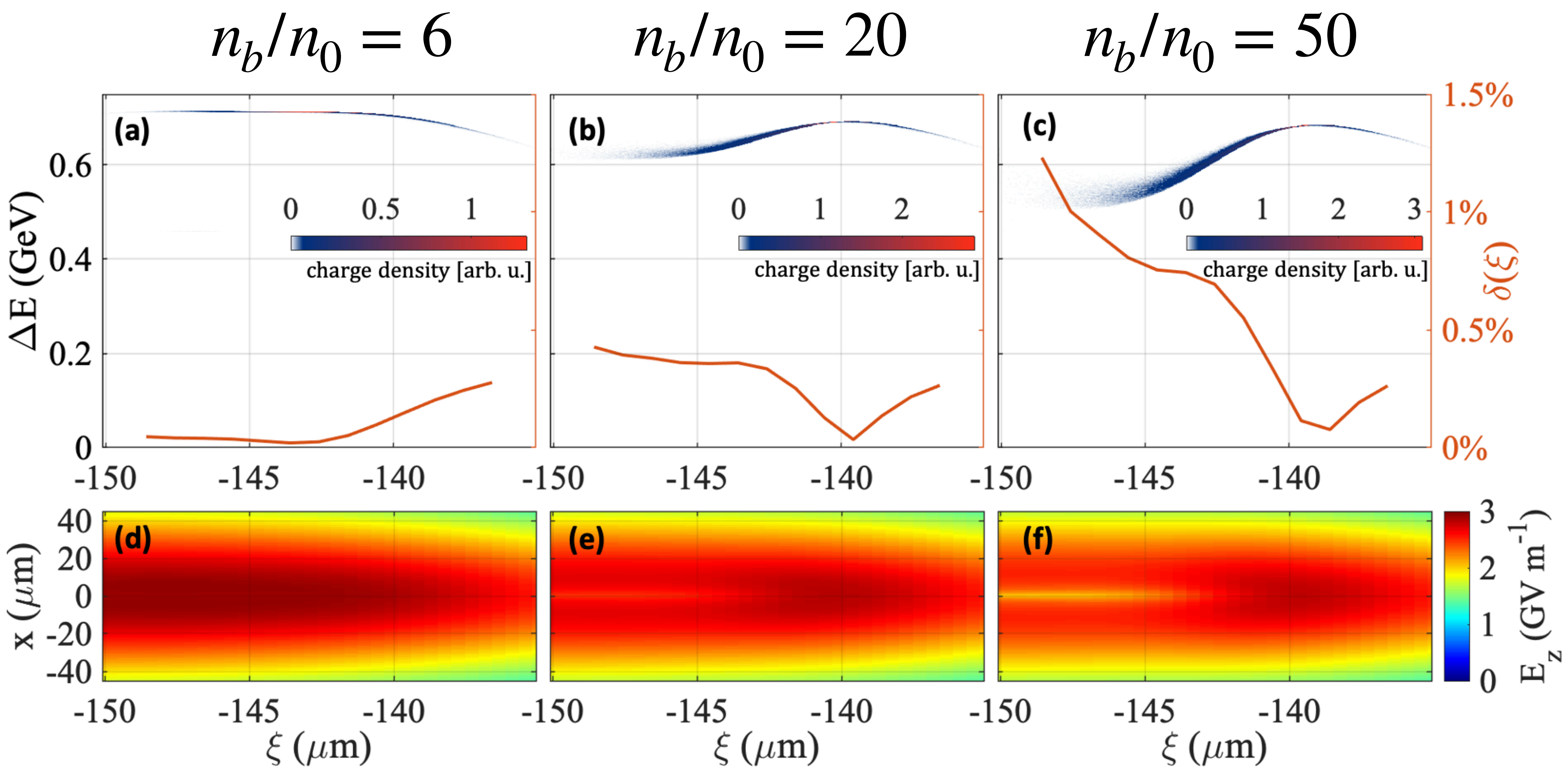


	σ_{tr} (μm)	ε_n (μm)	β (cm)	σ_{tz} (μm)	n_b/n_0	$k_b\sigma_{tz}$	E (GeV)	η (%)	$\Delta\varepsilon_n$ (%)
	0.7	0.5	0.20	2.14	1	0.09	1	0.30	27.6
	0.8	0.5	0.26	2.14	1	0.09	1	0.39	11.6
Fig. 3(a)	1.0	0.5	0.40	2.14	1	0.09	1	0.61	1.74
	1.6	0.5	1.02	2.14	1	0.09	1	1.55	55.4
	1.01	0.5	0.41	2.14	0.25	0.045	1	0.16	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

Uncorrelated energy spread in quasilinear regime

Evolution of longitudinal phase space

slice energy spread



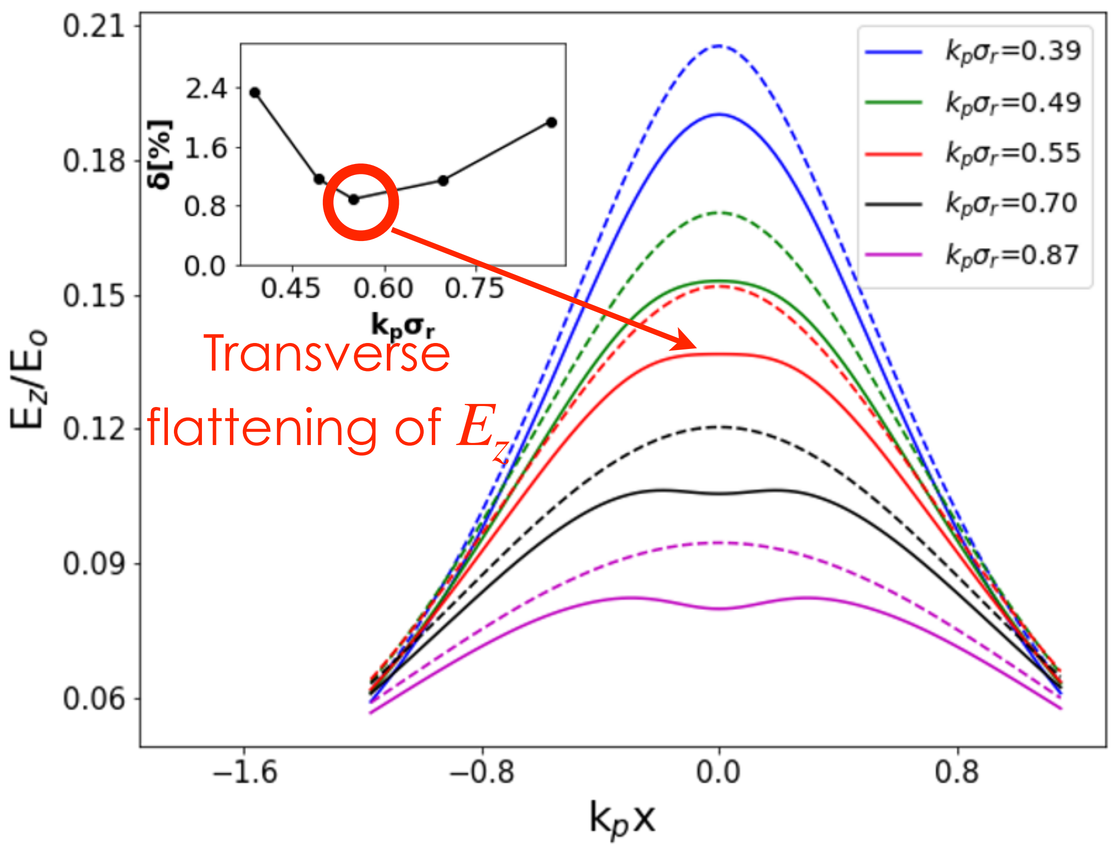
Two contributions to the energy spread:

- 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

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

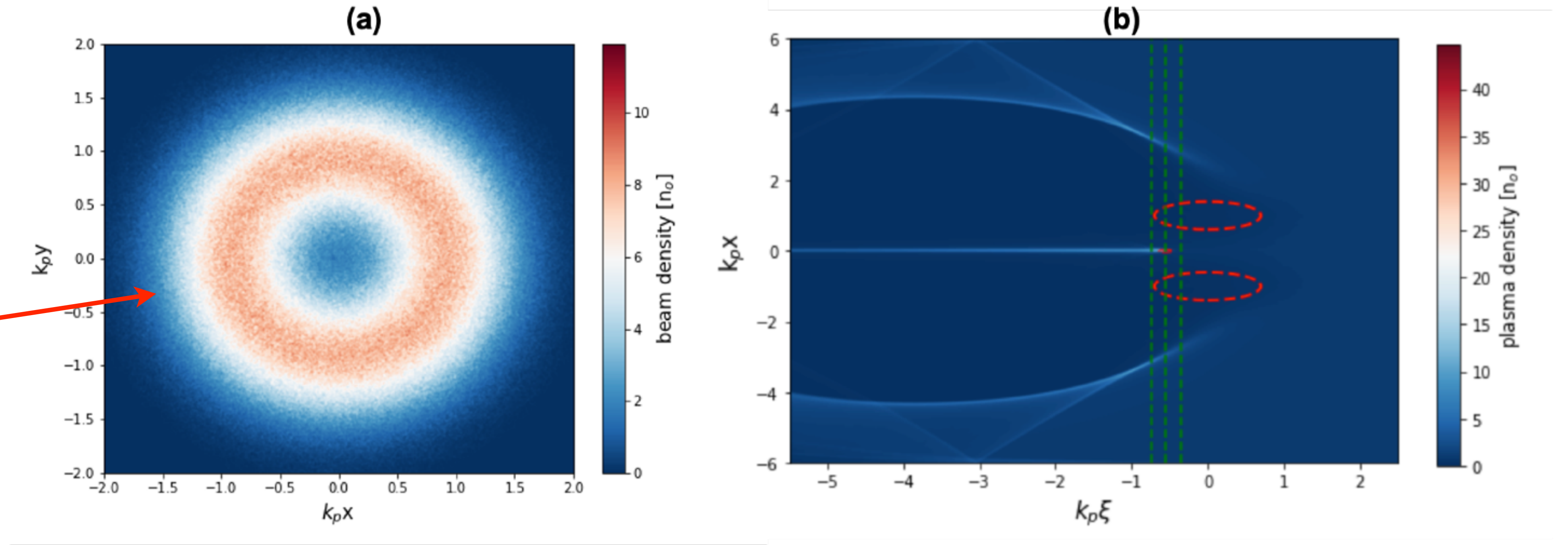
$$\eta_{p\to t} = \left| \frac{N_t \langle E_z \rangle_t}{N_d \langle E_z \rangle_d} \right|$$

- Re-optimize drive beam size for each value of the positron load
- Determine uncorrelated energy spread δ

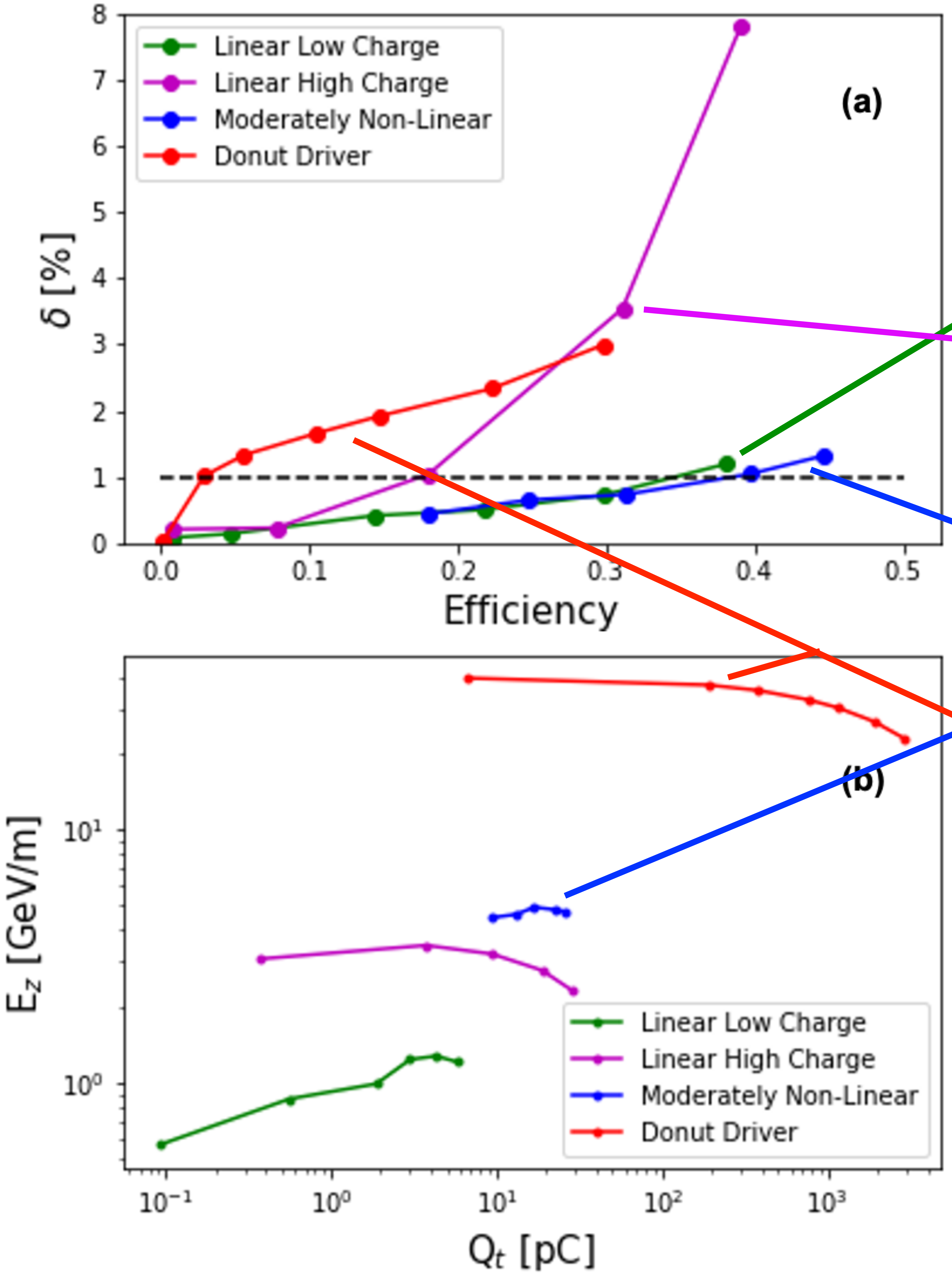
Note: quasi-matching here is ensured for micron-scale normalised emittance, plasma density is kept fixed at $5\ 10^{16}\ \mathrm{cm}^{-3}$

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



Energy efficiency η vs uncorrelated energy spread δ



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 $E_z \sim 1$ GV m^{-1}
- At higher drive charge (152 pC), drive beam size can no longer be optimised for $\eta \gtrsim 20\,\%$ because otherwise it becomes nonlinear. This results in large δ, unless the efficiency is limited to $\eta \lesssim 10\,\%$
- 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 $E_z \simeq 5$ GV m^{-1}.
- Nonlinear donut drivers: very high fields and positron charges, but degraded tradeoff between η and δ. Limited to $\eta \lesssim 5\,\%$ for $\delta \lesssim 1\,\%$.

	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

The positron problem

Plasma electron motion and transverse beam loading

The positron problem

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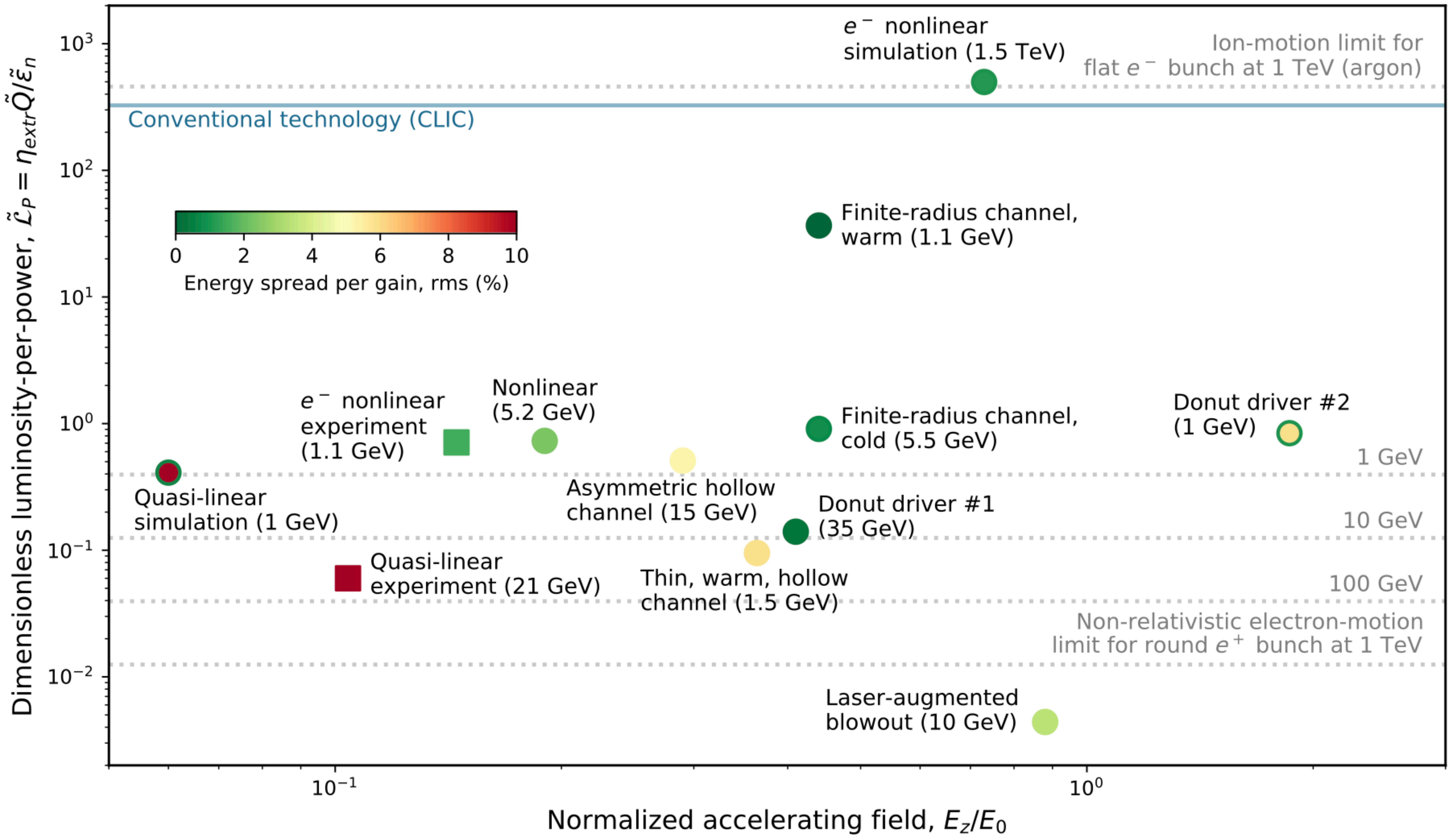
Plasma acceleration has emerged as a promising technology for future particle accelerators, particularly linear colliders. Significant progress has been made in recent decades toward high-efficiency and high-quality acceleration of electrons in plasmas. However, this progress does not generalize to the 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 energy efficiency and beam quality are summarized 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 nonuniform 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., PRAB 27, 034801 (2024)



The positron problem

Figure of merit:
luminosity per power

$$\mathscr{L} \approx \frac{fN^2}{4\pi\sigma_x\sigma_y} \approx \frac{1}{8\pi m_e c^2}\frac{P_{\text{wall}}}{\sqrt{\beta_x\epsilon_{nx}}}\frac{\eta N}{\sqrt{\beta_y\epsilon_{ny}}}$$

$$\frac{\mathscr{L}}{P_{\text{wall}}} \approx \frac{1}{8\pi m_e c^2}\frac{\eta_{\text{prod}}\eta_{\text{depl}}}{\sqrt{\beta_x\beta_y}}\boxed{\frac{\eta_{\text{extr}}N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}} = \alpha\tilde{\mathscr{L}}_P$$

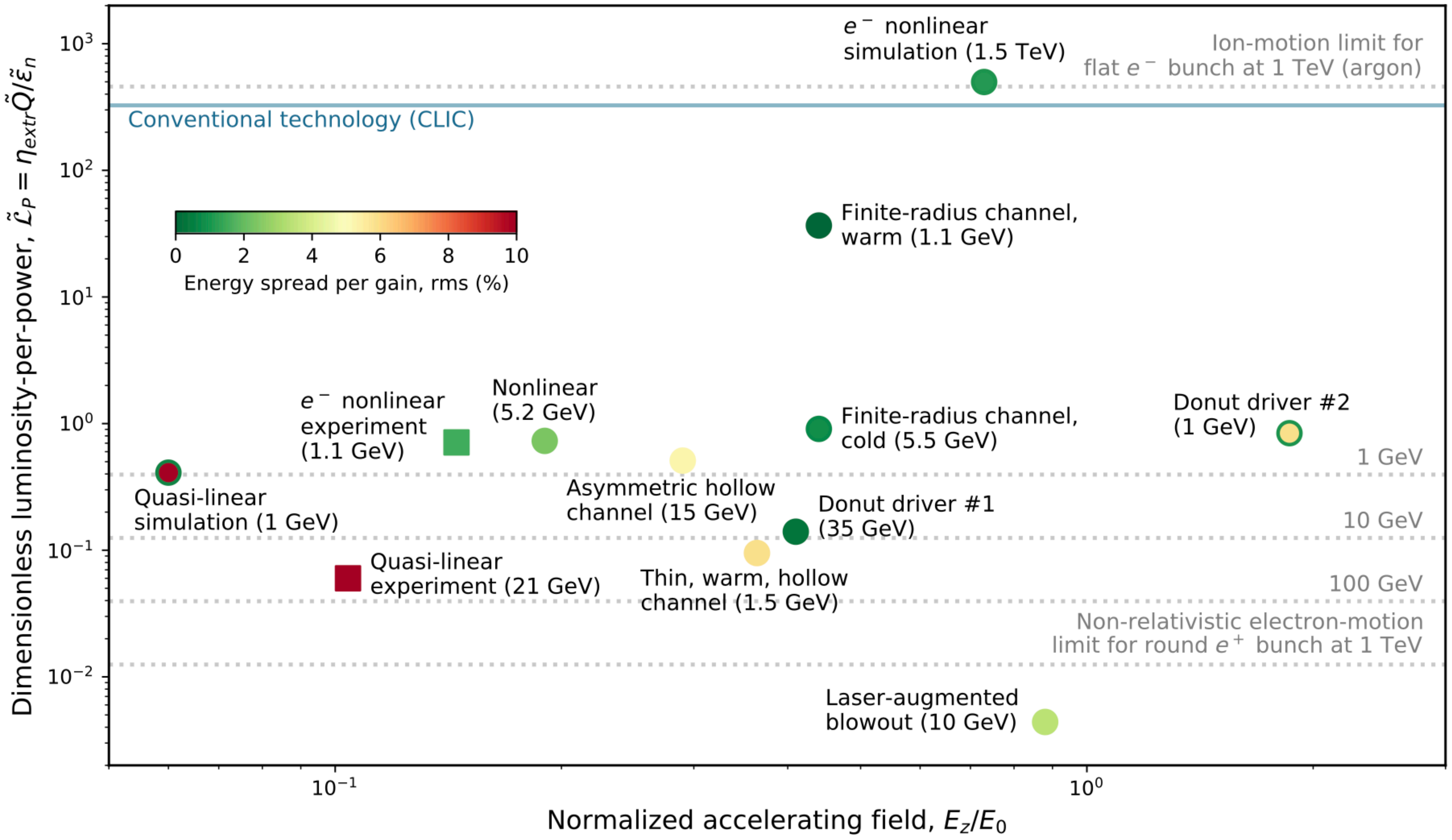
$$\boxed{\tilde{\mathscr{L}}_P = \frac{\eta_{\text{extr}}\tilde{Q}}{\tilde{\epsilon}_n}}$$

independent of plasma density

with:

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

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



Cao, Lindstrøm et al., PRAB 27, 034801 (2024)

The positron problem

Why such a gap between e- and e+?

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

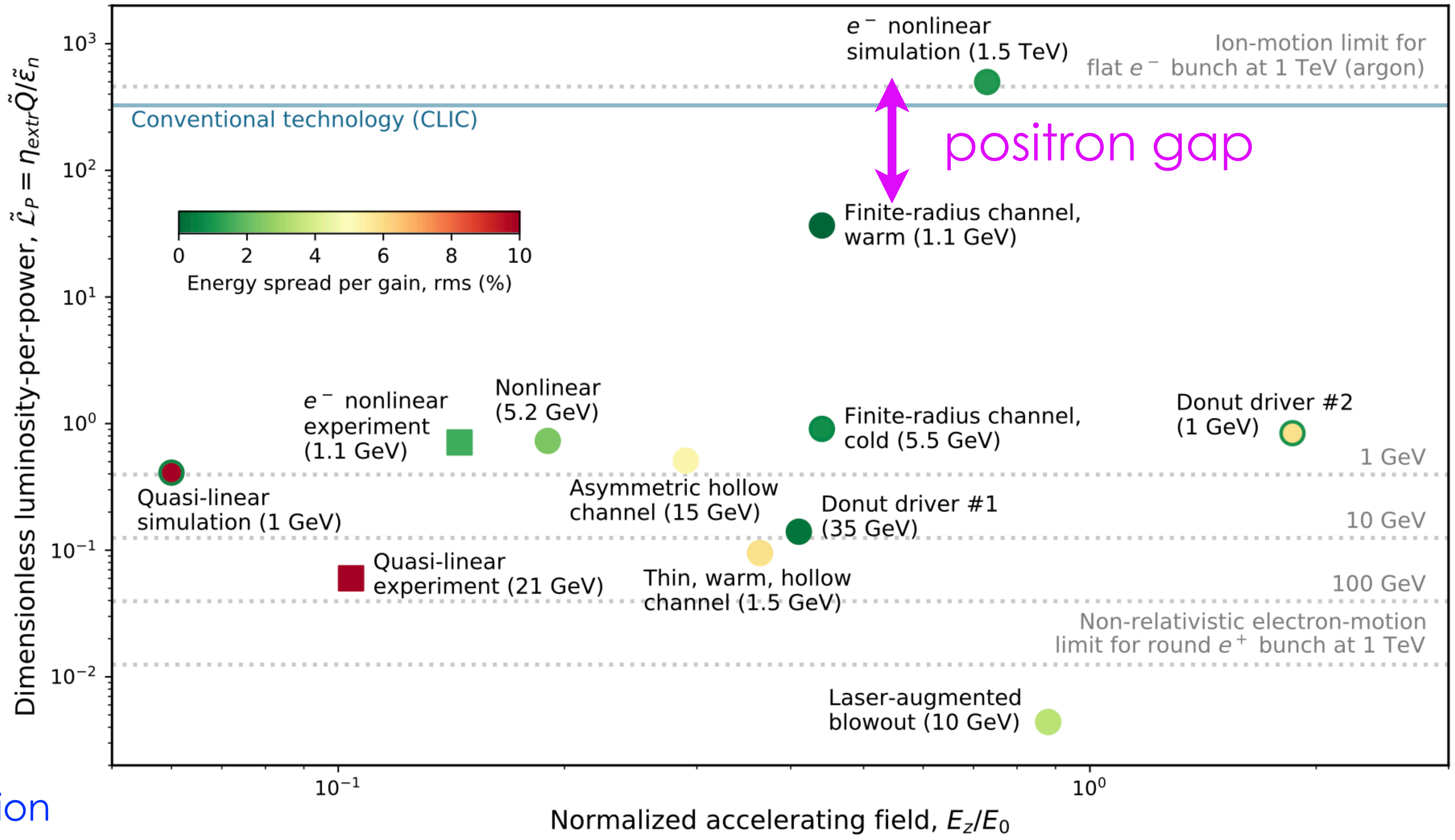
$$m_e \ll m_i$$

- 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

electron motion limit: $\Delta\phi_e \lesssim \pi/2$



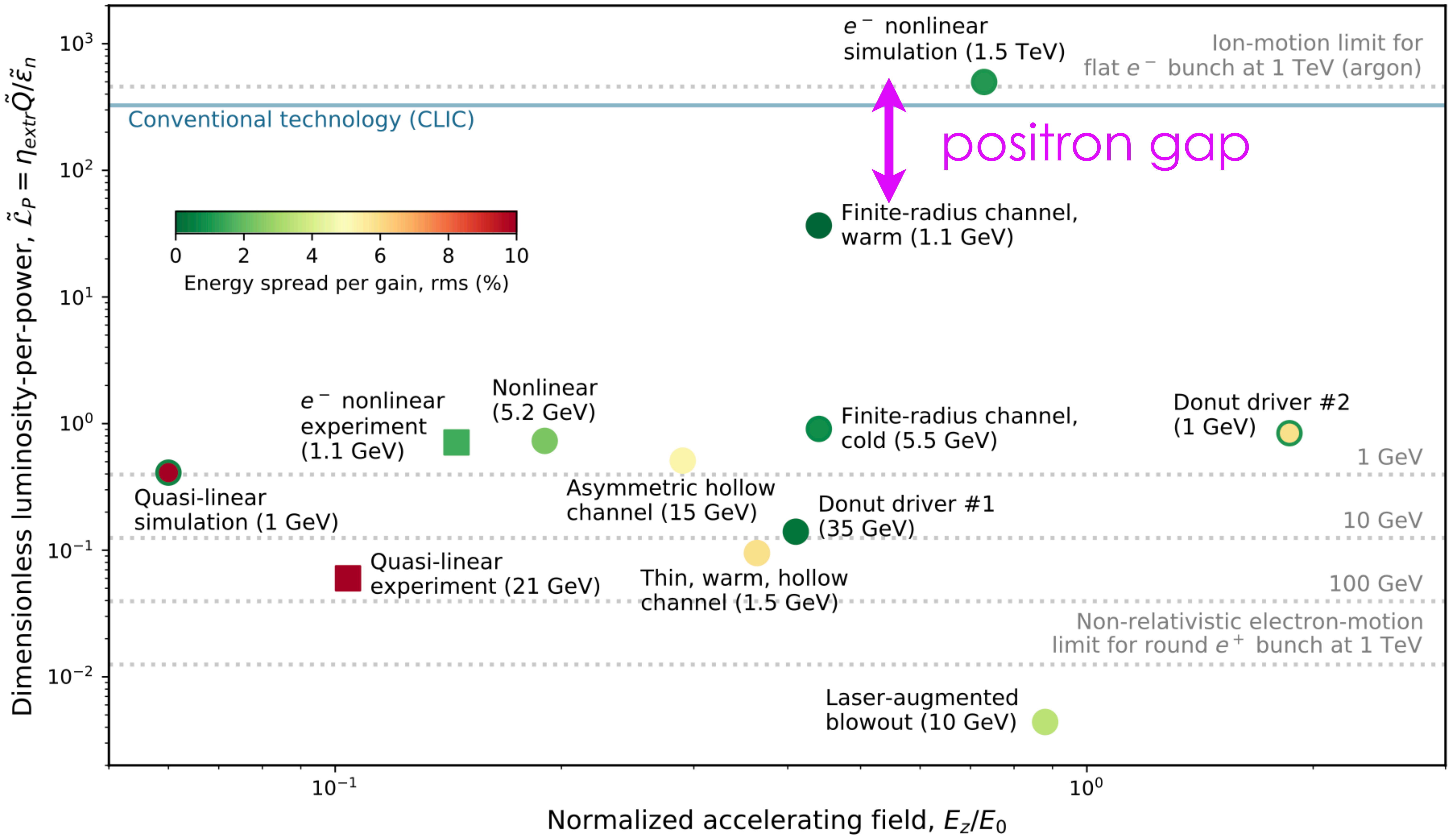
[Cao, Lindstrøm et al., PRAB 27, 034801 (2024)](#)

The positron problem

Electron motion limit embedded in luminosity-per-power

- Can rewrite $\tilde{\mathscr{L}}_P$ using $\Delta\phi_e$:

$$\tilde{\mathscr{L}}_P = \sqrt{\frac{16\pi}{\gamma}}(\Delta\phi_e)^2\left(\frac{\eta_{\mathrm{extr}}}{k_p\sigma_z}\right)\gamma_{pe}\sqrt{\frac{n_0}{\Delta n}}$$



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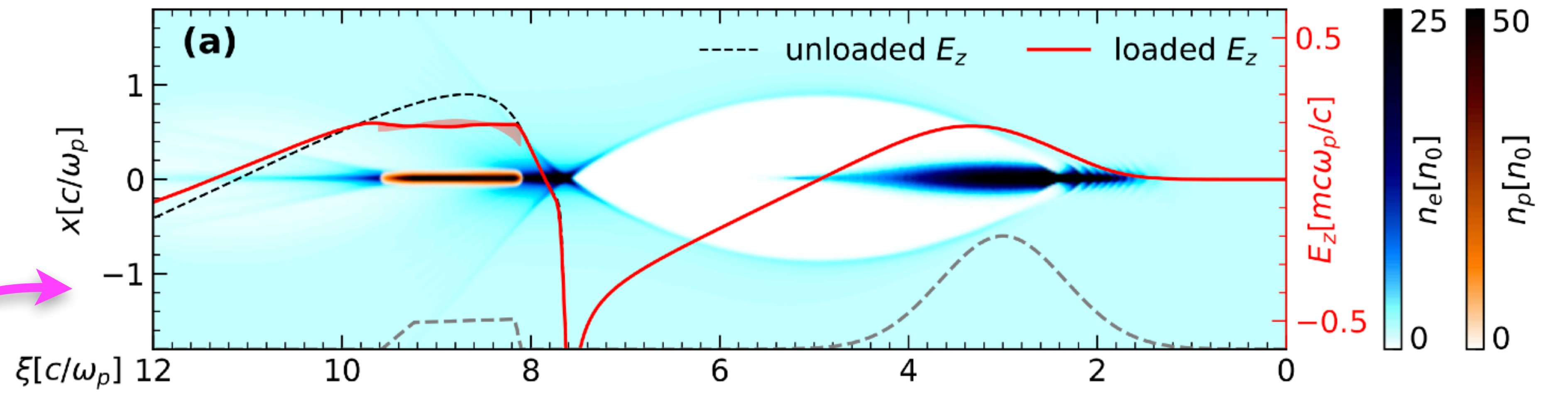
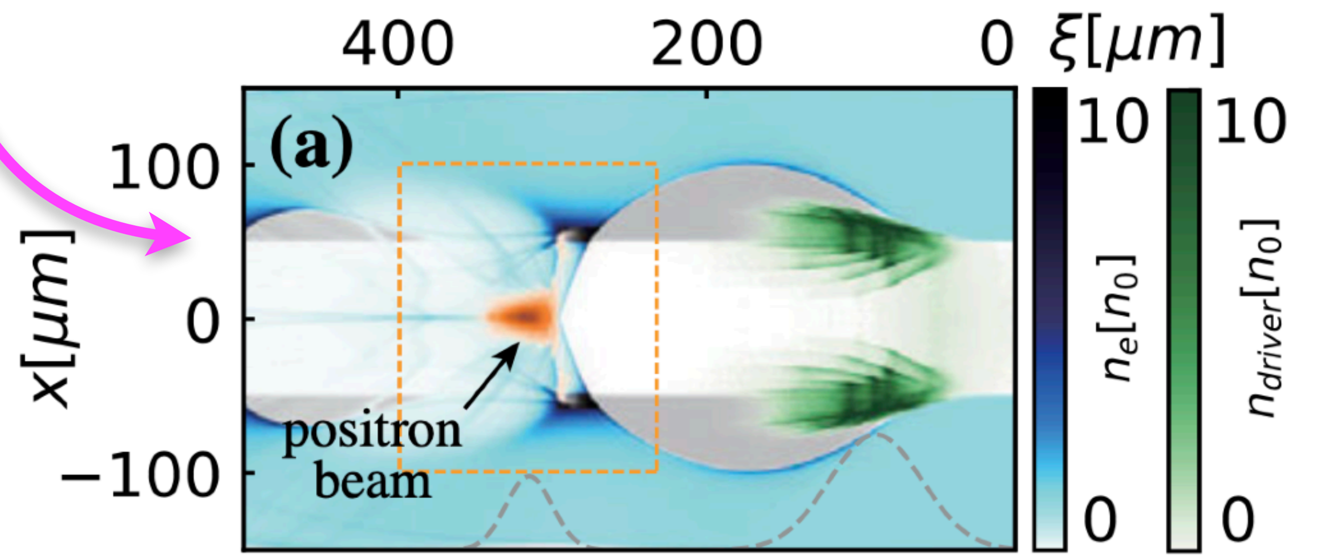
- What do we learn from e⁺ schemes:

Overcoming electron motion limit is a must

Charge and efficiency also important (favoring nonlinear regimes)



Scheme	Density (cm⁻³)	Gradient (GV/m)	Charge (pC)	Energy efficiency	Emittance (mm m rad)	Energy spread per gain	Uncorrected energy spread	Fin. energy (GeV)	$\Delta\phi_e$ [a]	Ref.
Quasilinear regime (simulation)	5×10^{16}	1.3	4.3	30%	0.64	~10% [b]	0.7%	1	0.77	[152]
Quasilinear regime (experiment)	1×10^{16}	1	85	40%	127 [c]	~14%	⋯	21	0.51	[87]
Nonlinear regime	7.8×10^{15}	1.6	102	26%	8	2.4%	⋯	5.2	7.6	[162]
Donut driver (No. 1)	5×10^{16}	8.9	13.6	0.17%	0.036	0.3%	⋯	35.4	0.50	[167]
Donut driver (No. 2)	5×10^{16}	40	189	3.5%	1.5 [d]	6%	1%	1	7.1	[152]
Finite-radius channel (cold)	5×10^{17}	30	52	3%	0.38	0.86%	0.73%	5.5	34	[180]
Finite-radius channel (warm)	5×10^{17}	30	84	4.8%	0.015	⋯ [e]	~0.01%	1.1	269	[181]
Laser-augmented blowout	2×10^{17}	20	15	5.5%	31	3.4%	⋯	~10	0.67	[187]
Thin, warm, hollow channel	1×10^{16}	3.5	100	4.7% [f]	7.4	6%	⋯	1.45	2.0	[188]
Asymmetric hollow channel	3.1×10^{16}	4.9	490	33%	67	5.3%	⋯	14.6	6.5	[189]
e^- nonlinear regime (simulation)	2×10^{16}	−10	800	37.5%	0.133 [g]	1.1%	≲1%	1500	292	[191]
e^- nonlinear regime (experiment)	1.2×10^{16}	−1.4	40	22%	2.8	1.6%	⋯	1.1	3.0	[192]
Conventional technology (CLIC)	Not applicable	0.1	596	28.5% [h]	0.11	0.35%	⋯	1500	Not applicable	[10]



Cao, Lindstrøm et al., PRAB 27, 034801 (2024)

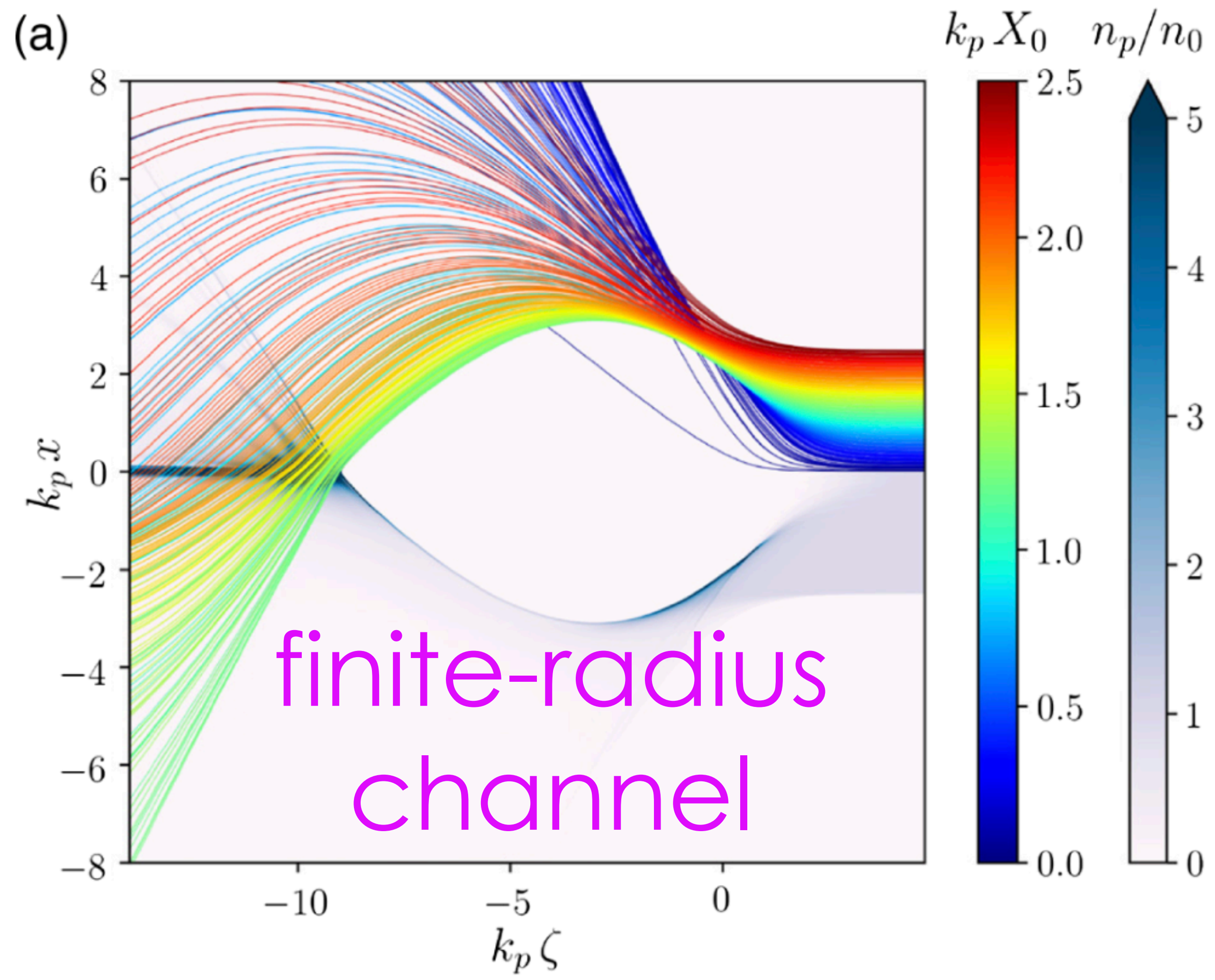
The positron problem

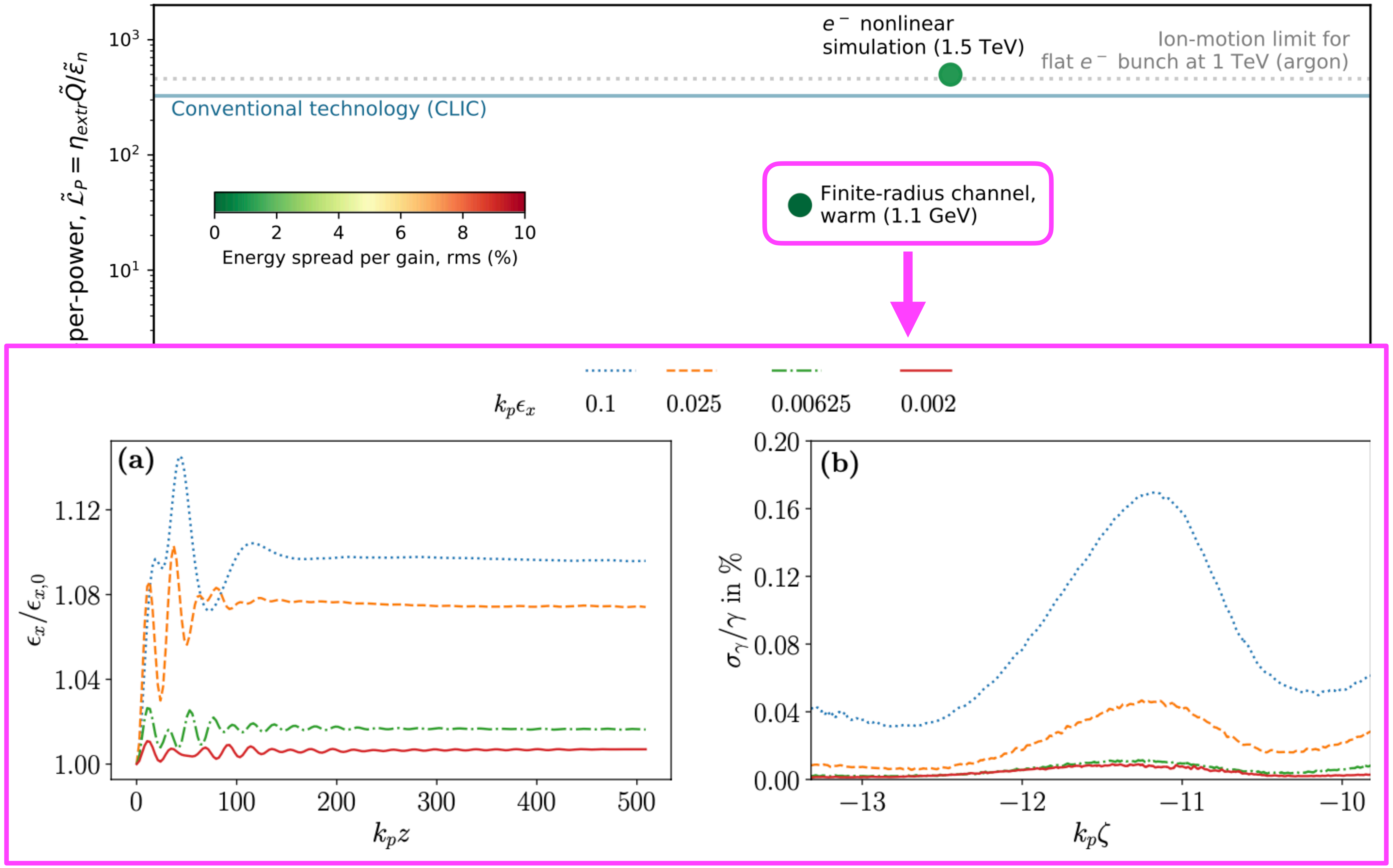
Strategies to fill the gap:

$$\tilde{\mathscr{L}}_P = \sqrt{\frac{16\pi}{\gamma}}(\Delta\phi_e)^2\left(\frac{\eta_{\rm extr}}{k_p\sigma_z}\right)\gamma_{pe}\sqrt{\frac{n_0}{\Delta n}}$$

$\Delta\phi_e$

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





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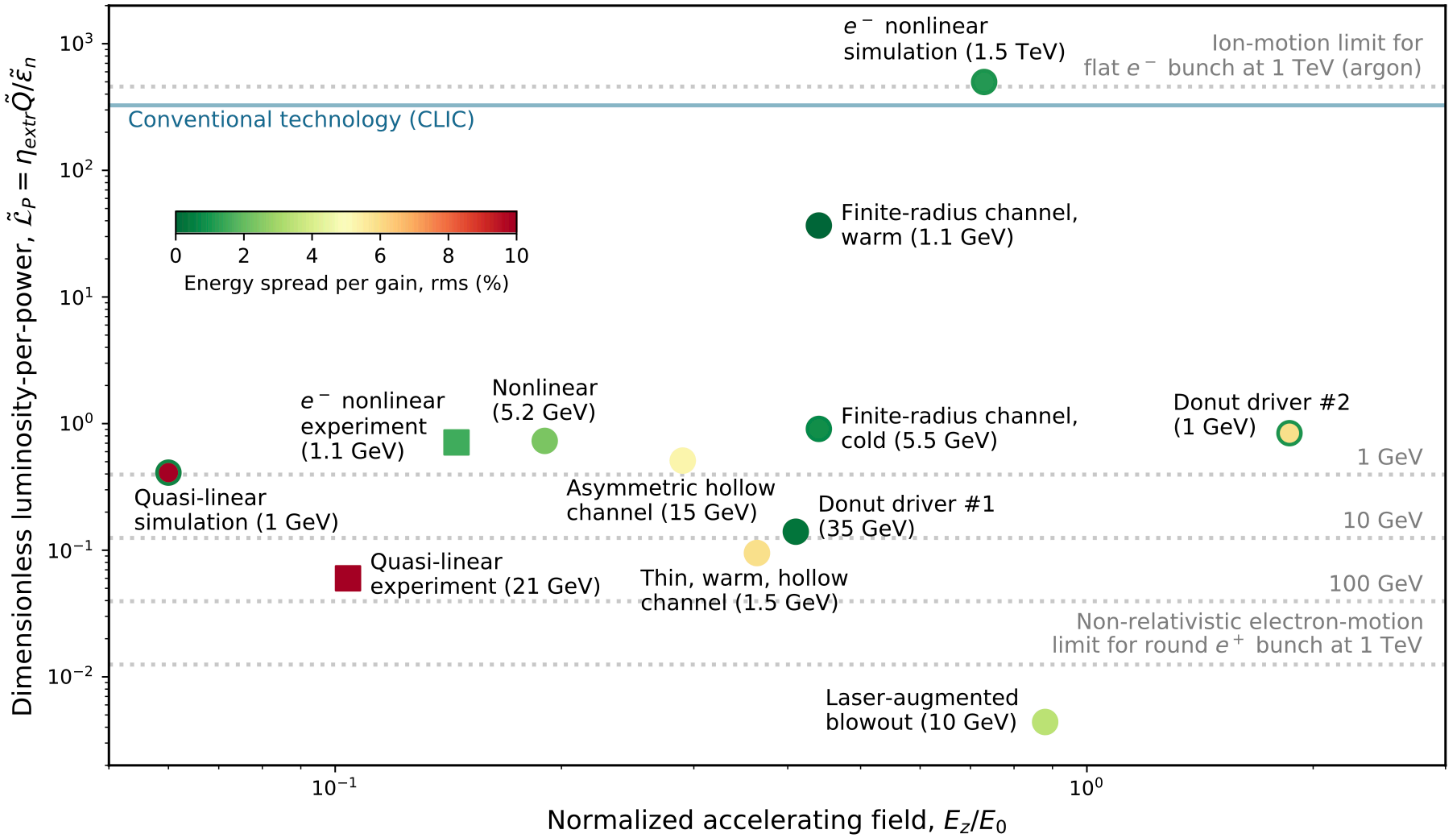
$\Delta\phi_e$

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

η_{extr}

- Energy recovery to improve efficiency
- Decrease emittance to compensate for low efficiency in $\tilde{\mathscr{L}}_P$

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



Conclusion

- Energy efficiency and luminosity-per-power comes with a strong positron load, and thus with transverse beam loading and electron motion

- 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