SLAC NATIONAL ACCELERATOR LABORATORY

# SLAC Intro

## e+ paper and the moderately non-linear regime (MNL)

Gevy Jiawei Cao

March 30, 2022

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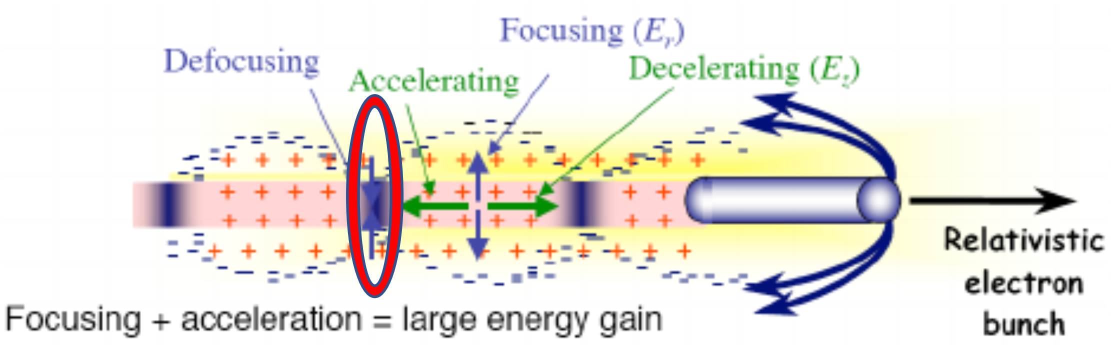
# e+ Regimes PWFA

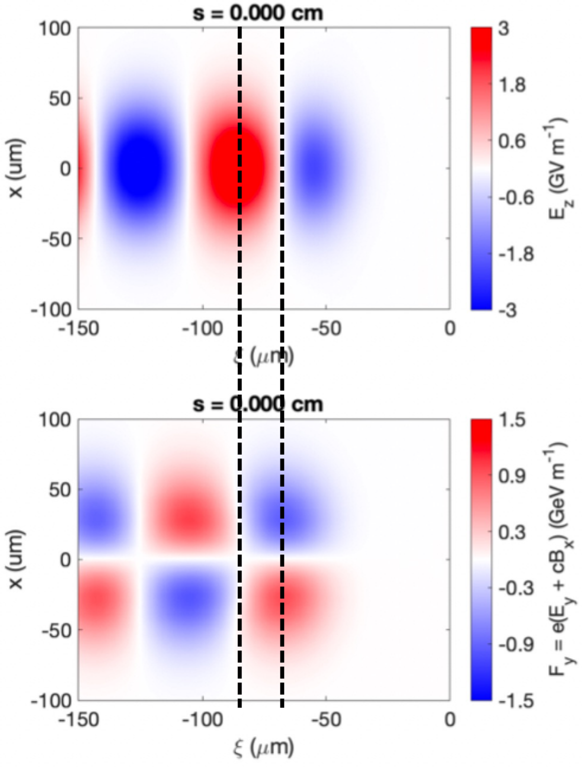
## Non-linear (bubble)



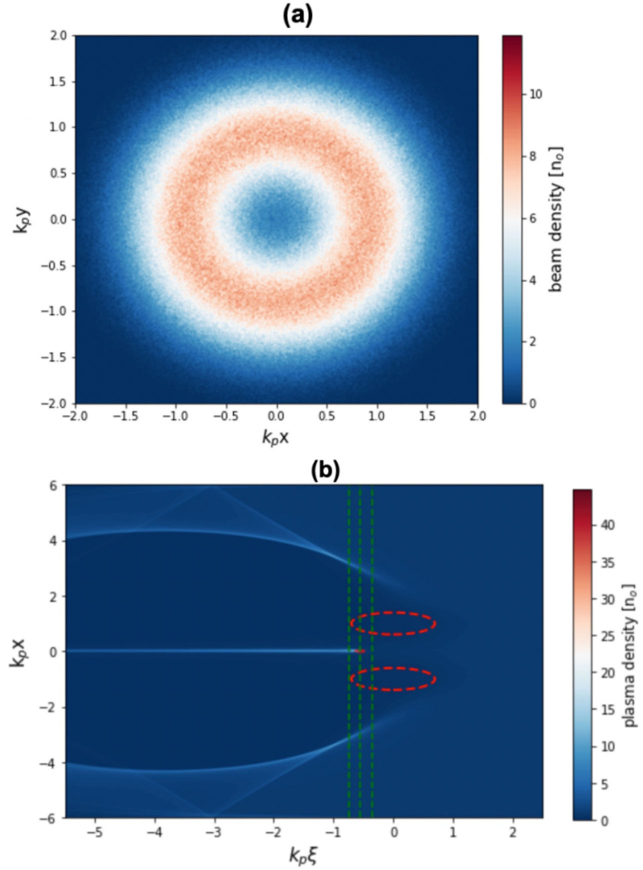
Focusing + acceleration = large energy gain

## Linear/quasi-linear ($\frac{n_b}{n_0} < 1$)

credit: Céline Hue

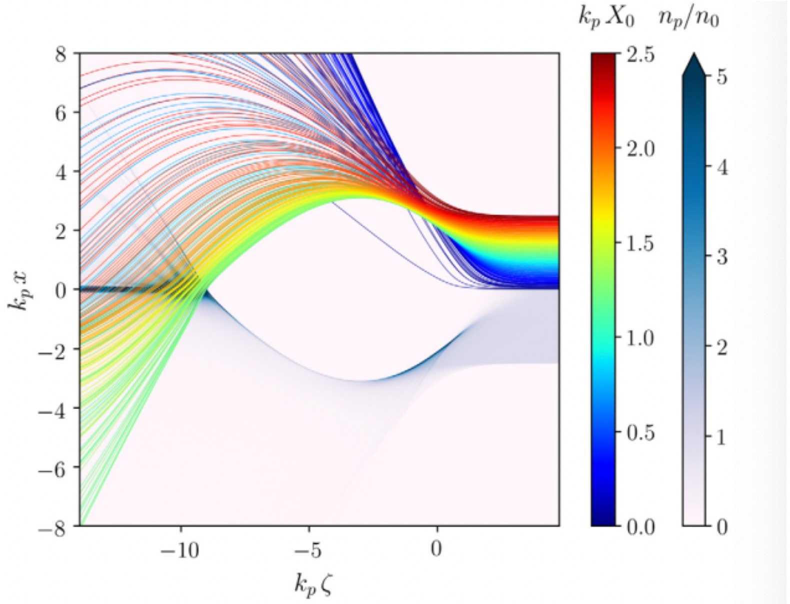


## Donut driver



T.Wang: arxiv 2110.10290(2021)

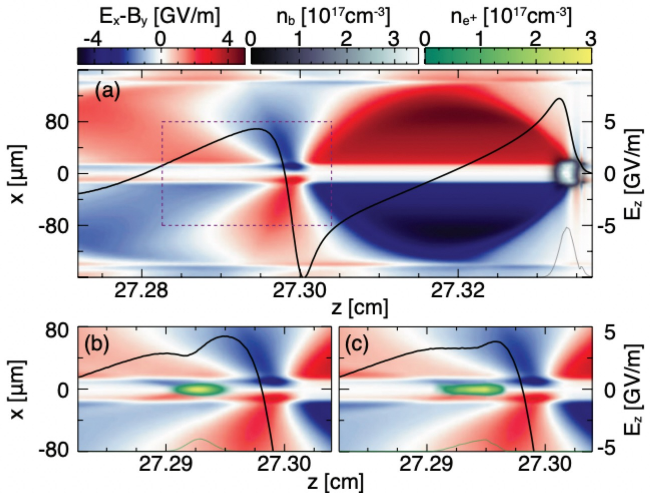
## Finite radius plasma



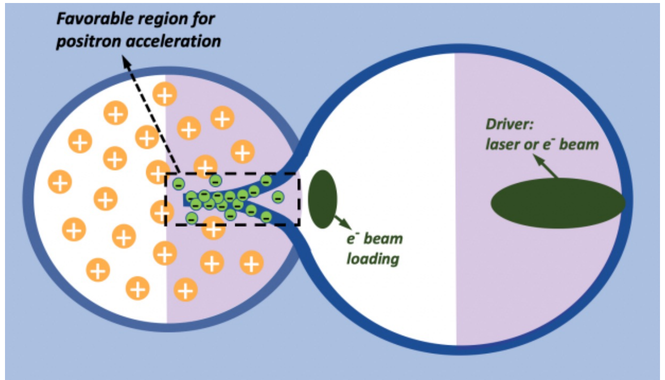
S.Diederichs: Phys.Rev.Acc 22,081301 (2019)

T.Silva: PRL 127, 104801 (2021)

## Warm hollow plasma channel



## Elongated bubble (non-linear)



# Assessment/Comparison criteria for eventual e-e+ collider application

- Drive-to-main efficiency: $\eta = \frac{E_{gain,main}}{E_{loss,drive}}$ > 10%
- e+ Beam Charge: $Q \geq 100pC$
- Acceleration gradient: $E_z > \frac{1GeV}{m}$
- Emittance $\epsilon_N = O(10mm \cdot \mu rad)$, with relative growth < 5%.
- Uncorrelated (slice/transverse) energy spread : $\delta < 1\%$
- Total energy spread: $\delta_{tot}$<10%

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

# Efficiency and beam quality for positron acceleration in loaded plasma wakefields

C. S. Hue,[1,*] G. J. Cao,[1,2,*] I. A. Andriyash,[1] A. Knetsch,[1] M. J. Hogan,[3] E. Adli,[2] S. Gessner,[3] and S. Corde[1,†]
[1] *LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France*
[2] *Department of Physics, University of Oslo, NO-0316 Oslo, Norway*
[3] *SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*

(Received 2 July 2021; accepted 1 October 2021; published 22 October 2021)

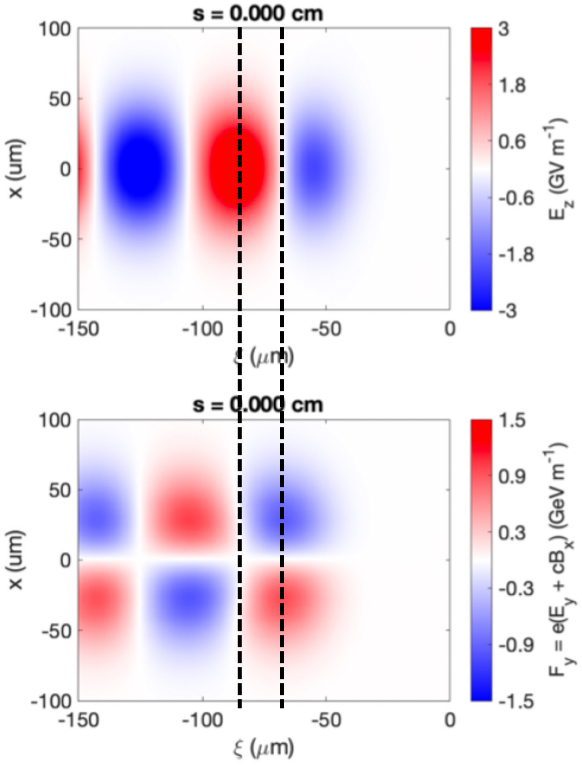
Accelerating particles to high energies in plasma wakefields is considered to be a promising technique with good energy efficiency and high gradient. While important progress has been made in plasma-based electron acceleration, positron acceleration in plasma has been scarcely studied and a fully self-consistent and optimal scenario has not yet been identified. For high energy physics applications where an electron-positron collider would be desired, the ability to accelerate positrons in plasma wakefields is, however, paramount. Here we show that the preservation of beam quality can be compromised in a plasma wakefield loaded with a positron beam, and a tradeoff between energy efficiency and beam quality needs to be found. For electron beams driving linear plasma wakefields, we have found that despite the transversely nonlinear focusing force induced by positron beam loading, the bunch quickly evolves toward an equilibrium distribution with limited emittance growth. Particle-in-cell simulations show that for $\mu$m-scale normalized emittance, the growth of uncorrelated energy spread sets an important limit. Our results demonstrate that the linear or moderately nonlinear regimes with Gaussian drivers provide a good tradeoff, achieving simultaneously energy-transfer efficiencies exceeding 30% and uncorrelated energy spread below 1%, while donut-shaped drivers in the nonlinear regime are more appropriate to accelerate high-charge bunches at higher gradients, at the cost of a degraded tradeoff between efficiency and beam quality.

DOI: 10.1103/PhysRevResearch.3.043063

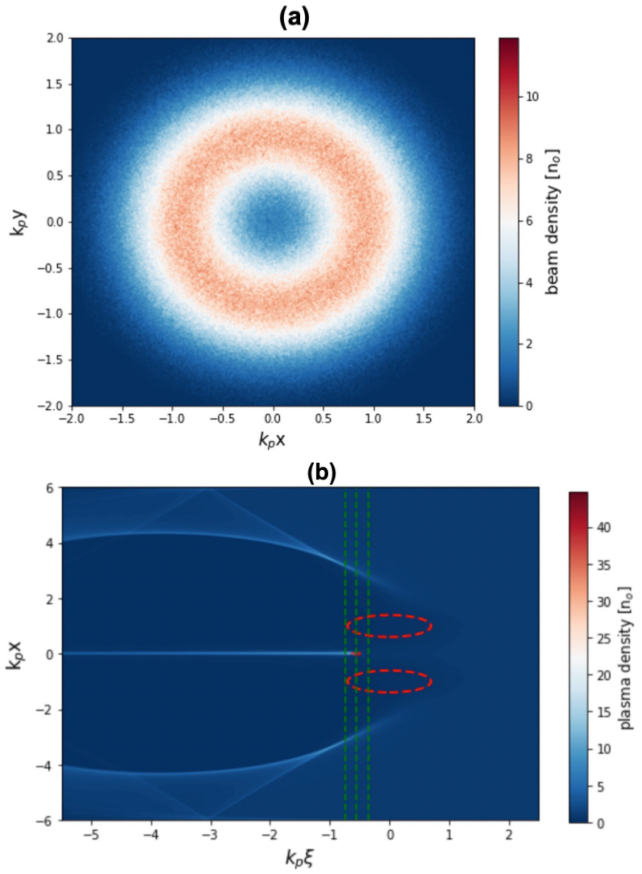
# Part I: Intro/Goal – compare several e+ regimes

- Focus: linear/quasi-linear and donut-driver (non-linear).
- Main criteria:
    - Drive-to-main efficiency: $\eta = \frac{E_{gain,main}}{E_{loss,drive}}$
    - Uncorrelated (slice/transverse) energy spread : $\delta$

Linear/quasi-linear ($\frac{n_b}{n_o} < 1$)



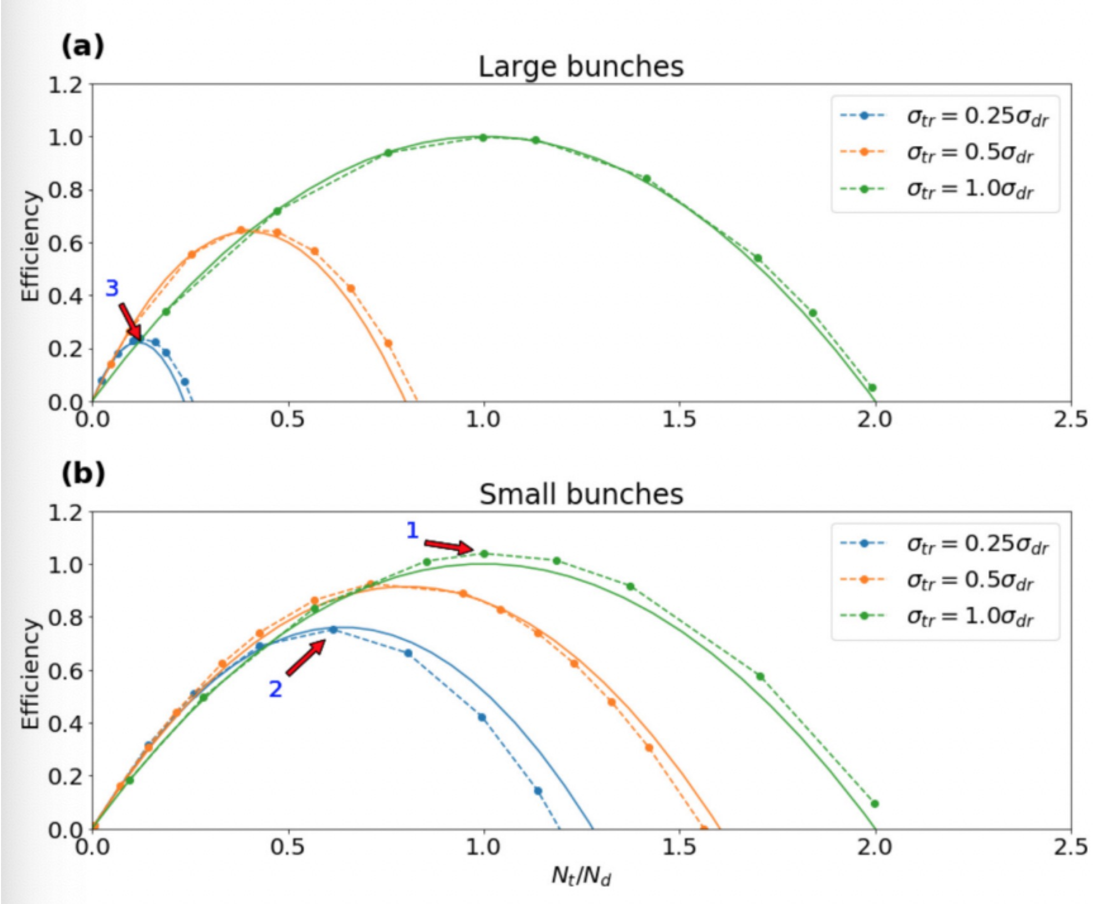
Donut driver



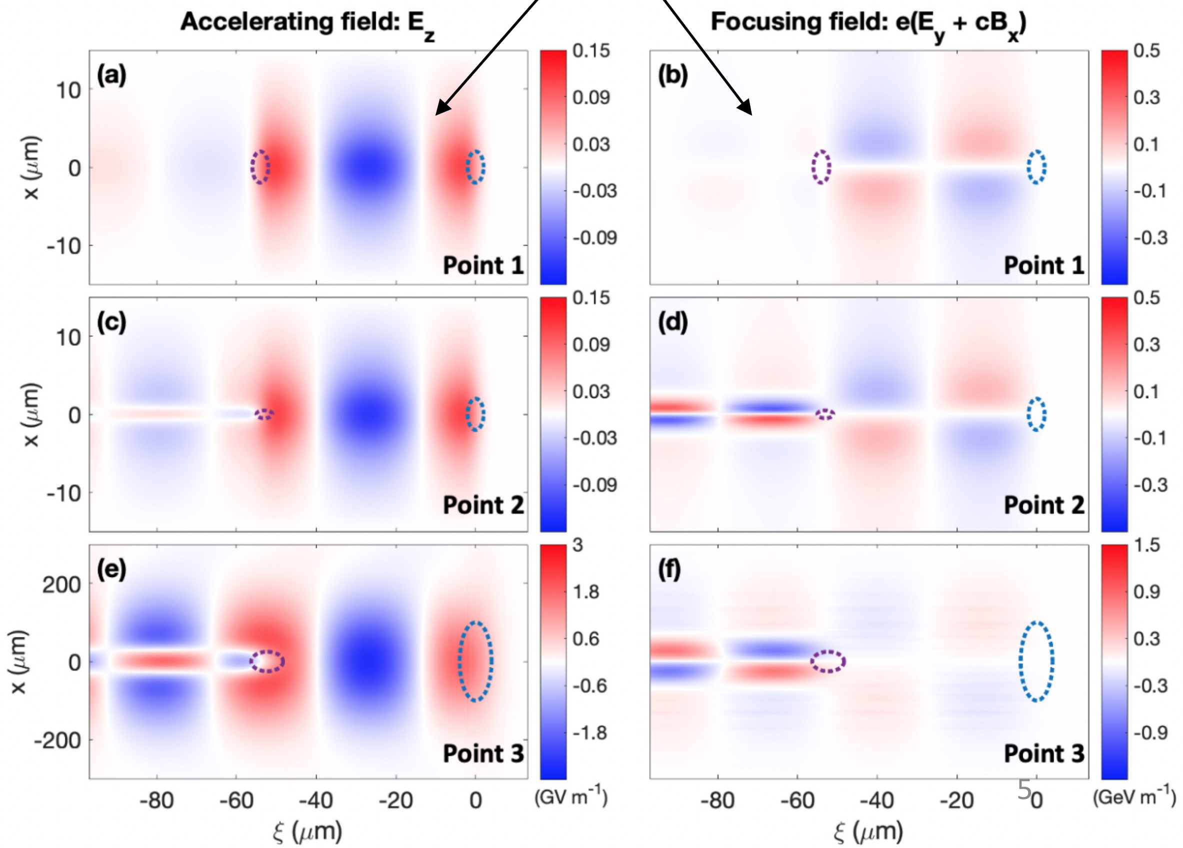
# Part II.A.: linear/quasi-linear regime

3D Analytical expression of the energy efficiency for a Gaussian e+ bunch with $k_p \sigma_r \gg 1$:

$$\eta = \frac{N_t}{N_d}\frac{\sigma_{dr}^2}{\sigma_{tr}^2}\left[\frac{4}{1+\frac{\sigma_{dr}^2}{\sigma_{tr}^2}} - \frac{N_t}{N_d}\right]$$



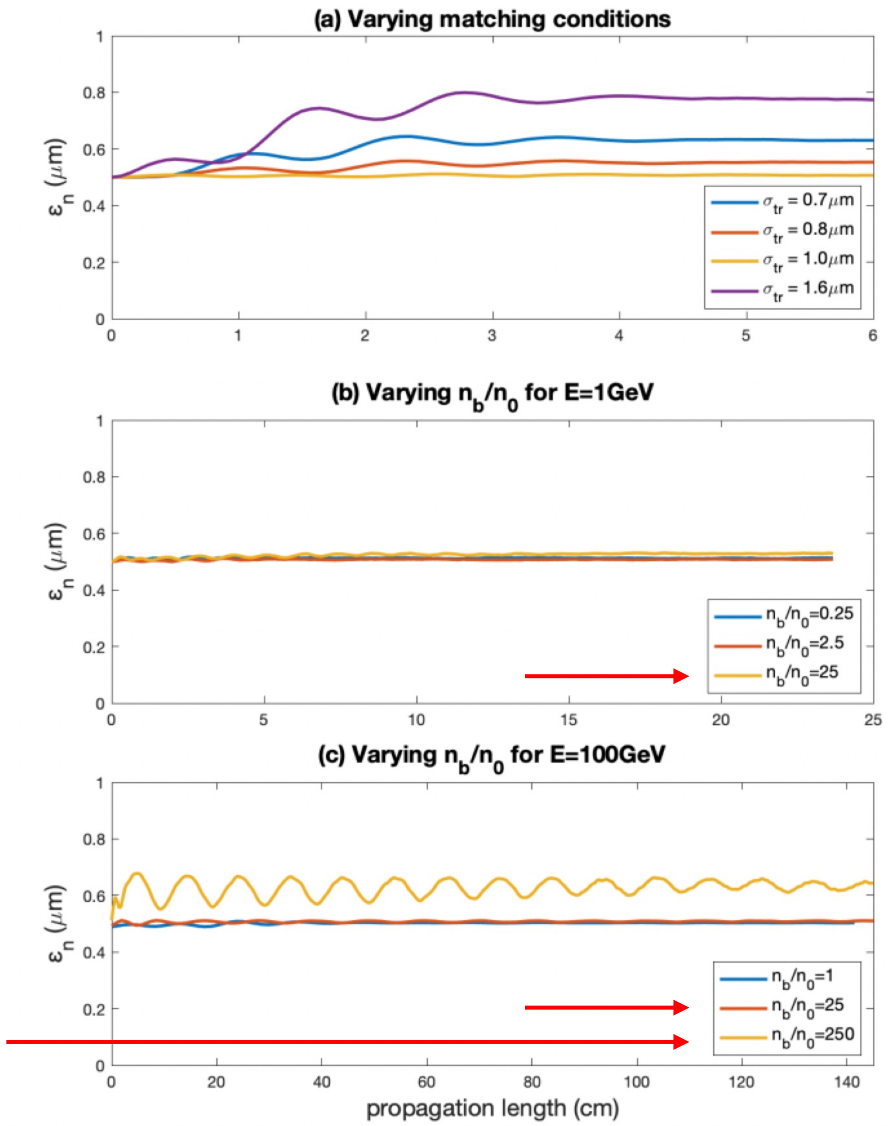
**Pt 1 optimal**



# Part II.B.: linear/quasi-linear regime

- Emittance equilibrium can be achieved after some propagation distance by quasi-matching, and emittance growth is relatively small when $k_b\sigma_z \ll 1$.

- Remarkably, this is true even if $n_b \gg 1$.



$k_b\sigma_z > 1, \Delta\epsilon \cong 30\%$

# Part II.C.: Uncorrelated energy spread as an important limit

- Correlated energy spread problem can be addressed by beam loading/dechirping etc. Uncorrelated energy spread not removable. Beam loading can greatly affect this parameter.
- Slice energy spread defined as:

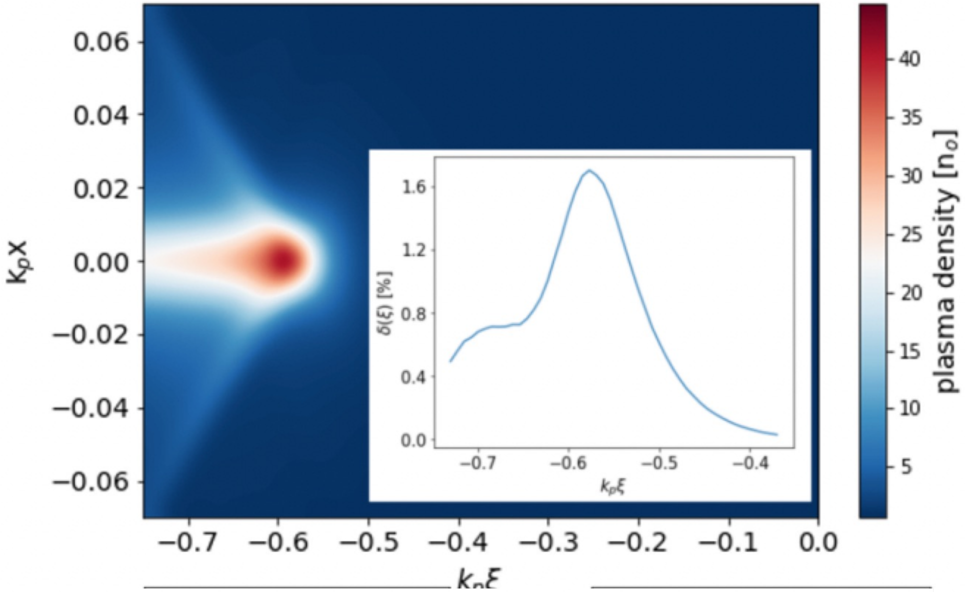
$$\delta(\xi) = \frac{\Delta E_{final}(\xi)}{< E_{final} > (\xi) - E_{init}}$$

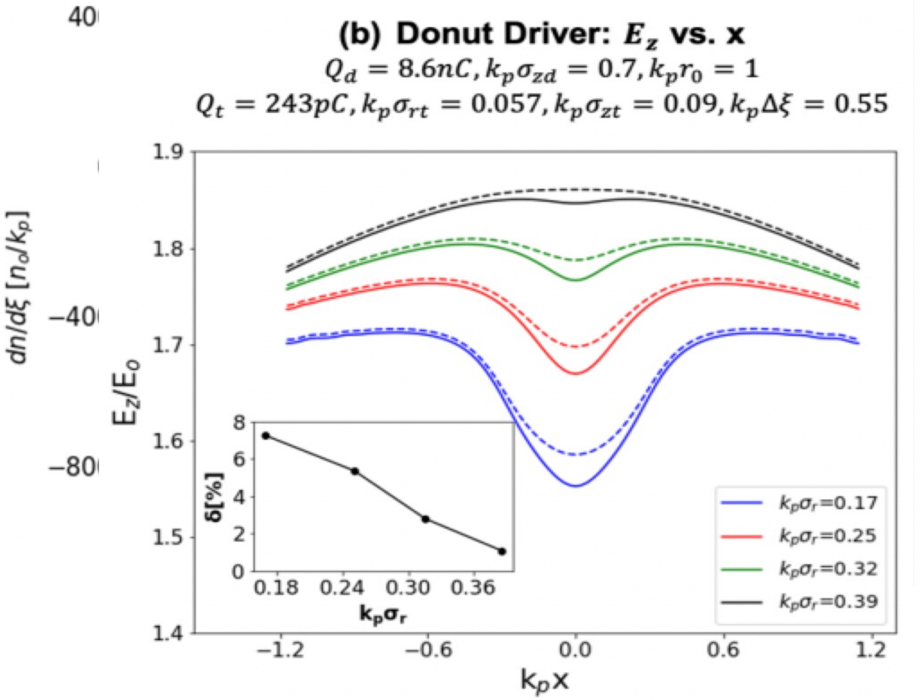
- Uncorrelated energy spread :

$$\delta = \frac{\int [\delta(\xi) \int (n_t dxdy)] d\xi}{N_t}$$

# Part III: Donut driver

- High charge, low efficiency
- Limitation by $\delta$:
  - Ideal case: $\partial_\xi F_r = \partial_r F_z = 0$
  - Ignoring ion motion, main source of $F_z$ / $F_r$ comes from the plasma e-.
  - High e+ charge strongly loads the field, rendering the above condition impossible.
- Optimal donut driver: large $\sigma_r$ to introduce a more uniform on-axis plasma e-





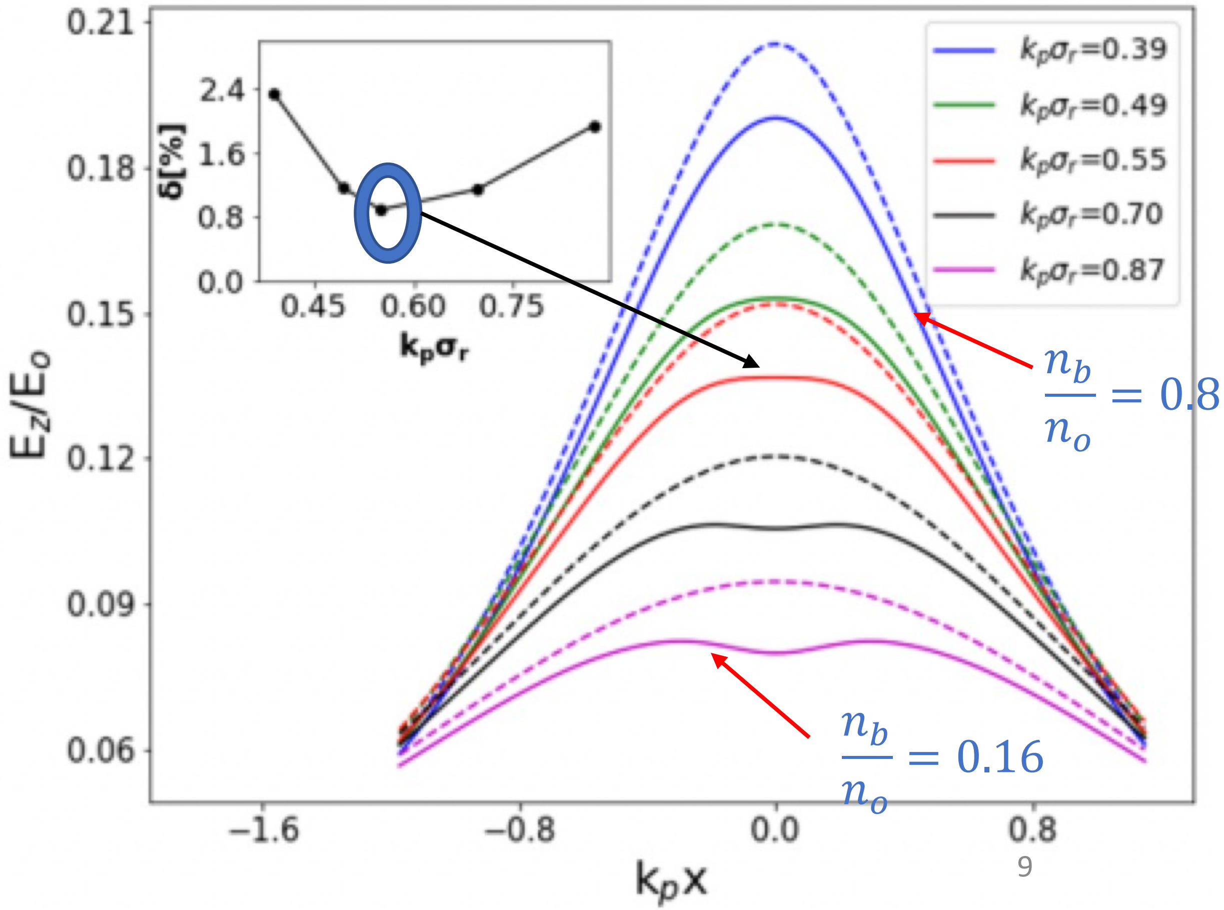
# Part IV.A.: Driver optimization

- Optimizing $\delta$ for a given e+ bunch
- For larger e+ charges → smaller driver → partial blow-out → moderately non-linear regime

**(a) Linear regime: $E_z$ vs. x**

$Q_d = 152pC, k_p\sigma_{zd} = 0.7$

$Q_t = 11.4pC, k_p\sigma_{rt} = 0.11, k_p\sigma_{zt} = 0.09, k_p\Delta\xi = 6.2$



$\frac{n_b}{n_o} = 0.8$

$\frac{n_b}{n_o} = 0.16$

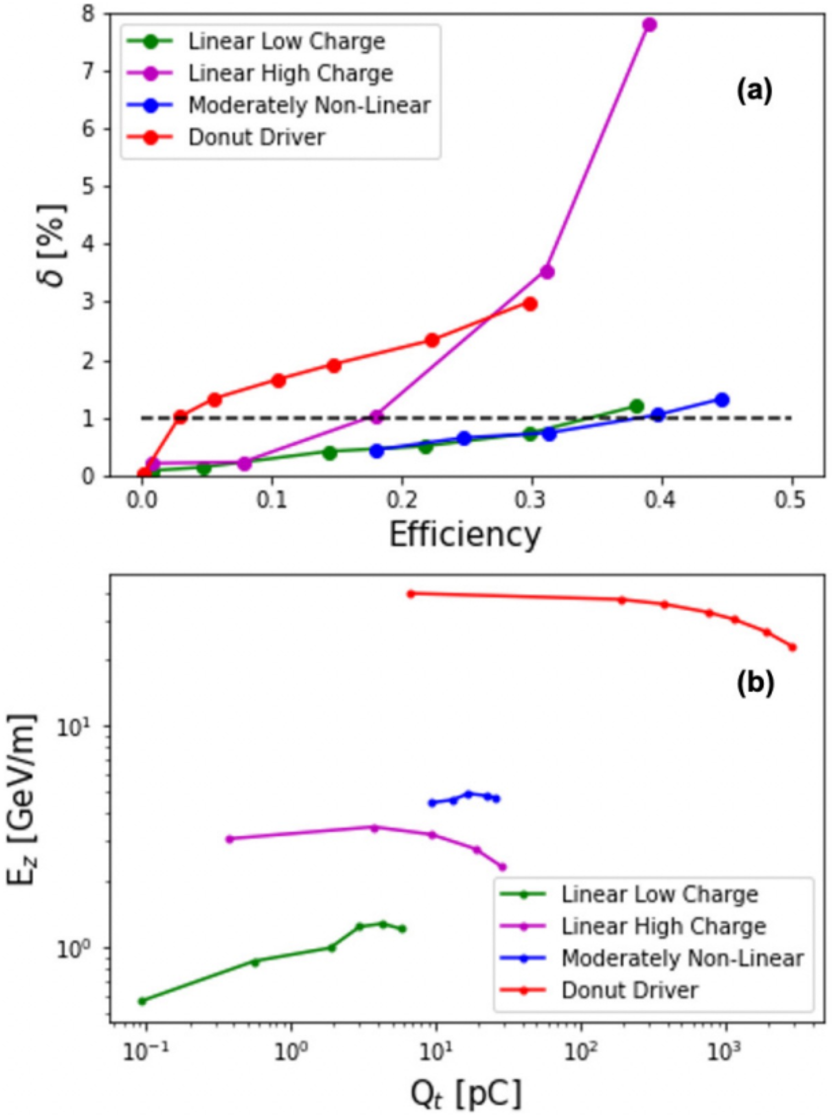
# Part IV.B.: Regime comparison

## $\eta - \delta$ trade-off

**Requiring $\delta$<1%:**

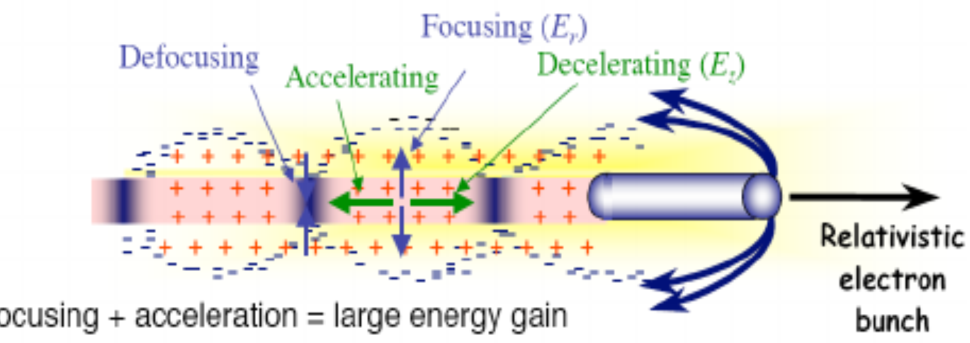
- Linear low charge: O(pC) e+, 1 GeV/m, 30% efficiency
- Linear high charge: O(10 pC) e+, 3 GeV/m, 20% efficiency
- MNL: O(10 pC) e+, 5 GeV/m, 40% efficiency
- Donut driver: O(100 pC) e+, 20 GeV/m, 3% efficiency

→ MNL has the potential to achieve high $\eta$ and low $\delta$ simultaneously



# MNL (work done after the paper)

Non-linear (bubble, $\frac{n_b}{n_o} \gg 1$)

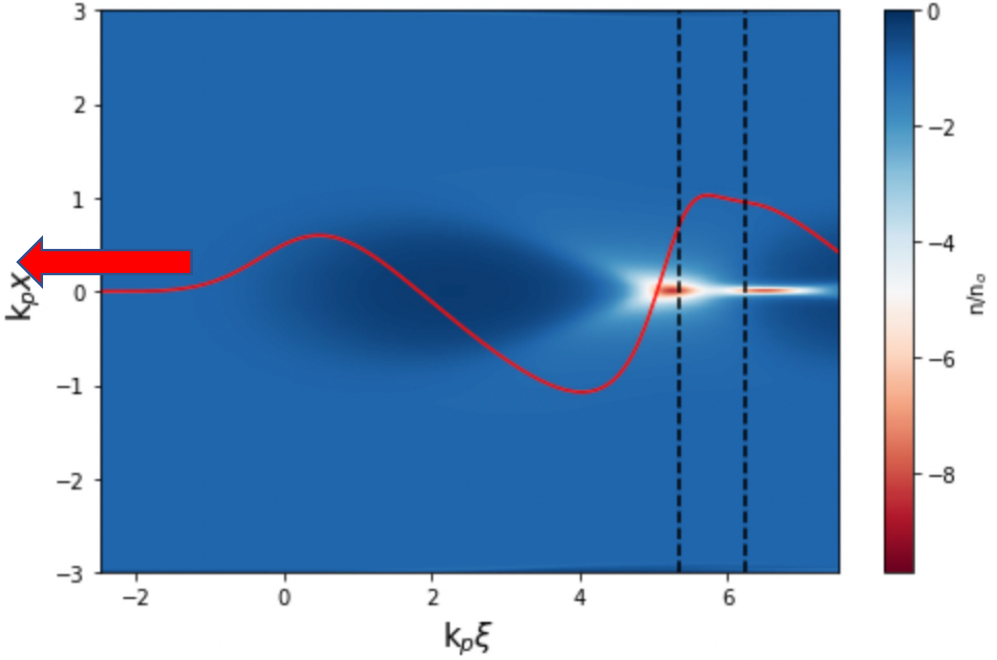


**Challenges**: high plasma e-density, short usable region.

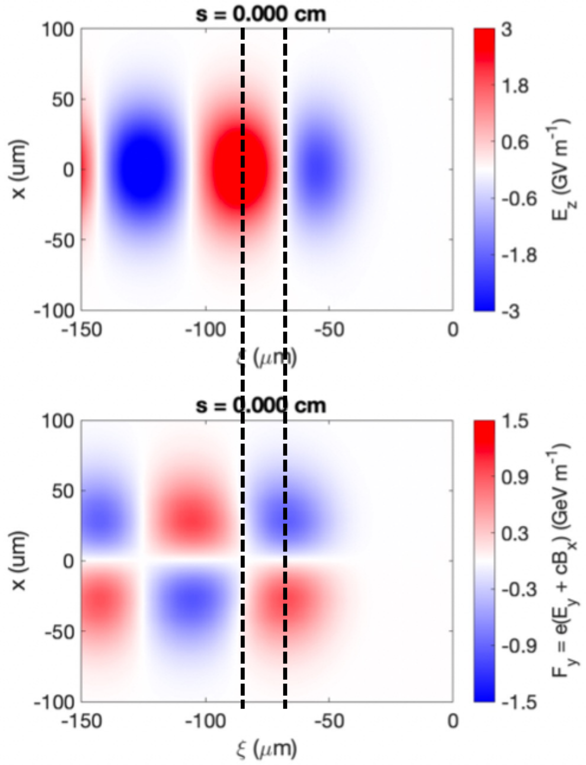
Questions unanswered in the paper:

- What about emittance growth in MNL?
- A more holistic assessment of beam quality, charge and efficiency

MNL ( $\frac{n_b}{n_o} \cong 1$)



Linear/quasi-linear ($\frac{n_b}{n_o} \ll 1$)



**Challenges**: low Q, low $E_z$, low $\eta$

# Assessment/Comparison criteria

- Drive-to-main efficiency: $\eta = \frac{E_{gain,main}}{E_{loss,drive}}$ > 10%
- Uncorrelated (slice/transverse) energy spread : $\delta < 1\%$
- e+ Beam Charge: $Q \geq 100pC$
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- Emittance $\epsilon_N = O(10mm \cdot \mu rad)$, with relative growth < 5%.
- Total energy spread: $\delta_{tot}$<10%

# Optimal MNL point

- After optimization, optimal MNL point at $\epsilon_N = 2.4mm \cdot mrad$ with emittance perservation:

| $n_{\{d,peak\}} = 1.0n_o, \sigma_{zd} = 16.7um, \sigma_{rd} = 8.6um$ | |
|---|---|
| $\eta$ [%] | 15 |
| $E_z$ [GeV/m] | 4.2 |
| $Q_t$ [pC] | 7.5 |
| $\delta$ [%] | 1.1 |
| $\delta_{tot}$ [%] | 8.1 |
| **$\Delta\epsilon$ [%]** | **5** |

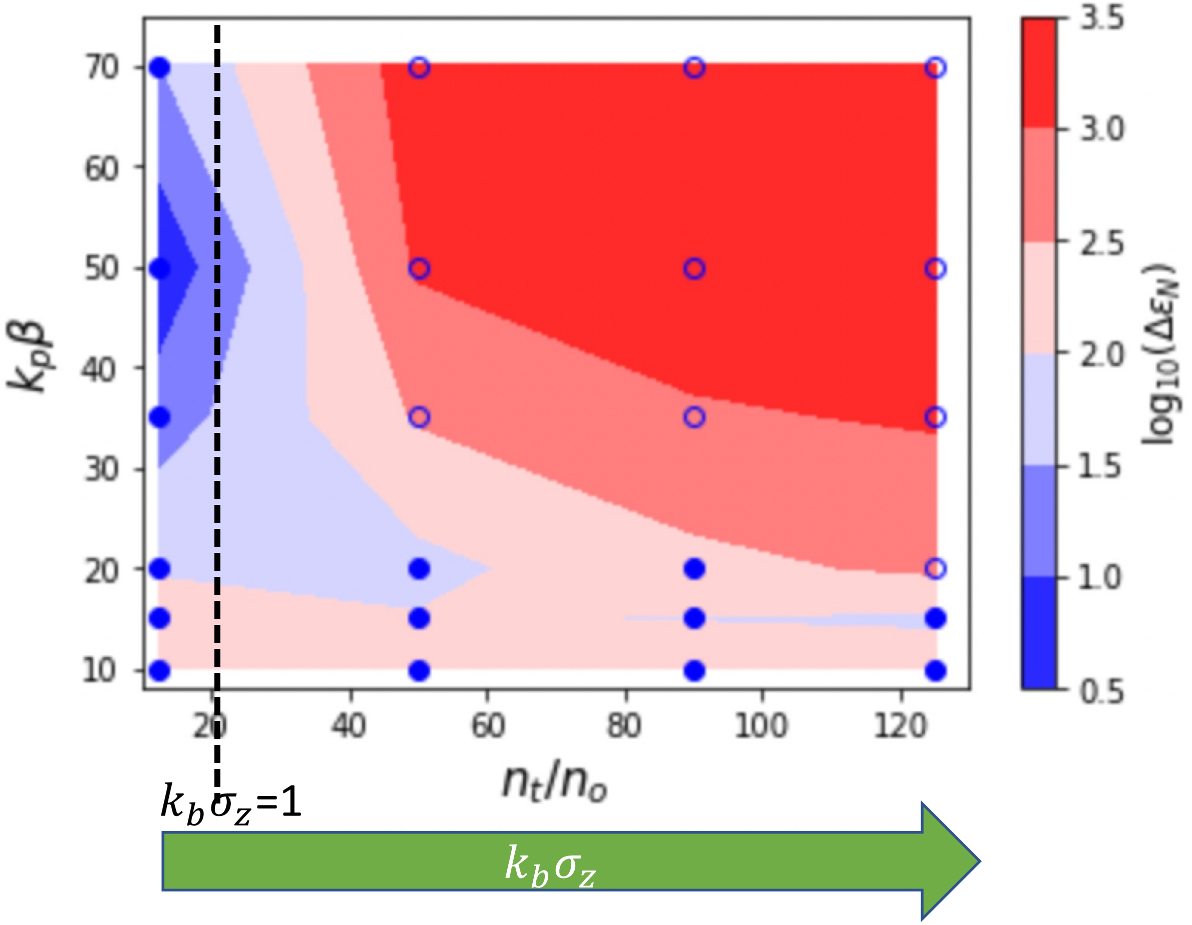
Question: What if we scale down the emittance to nm?

# Emittance scaling

$\epsilon_N = 0.24\, mm \cdot mrad$

Again limited by $k_b\sigma_z$ ☹

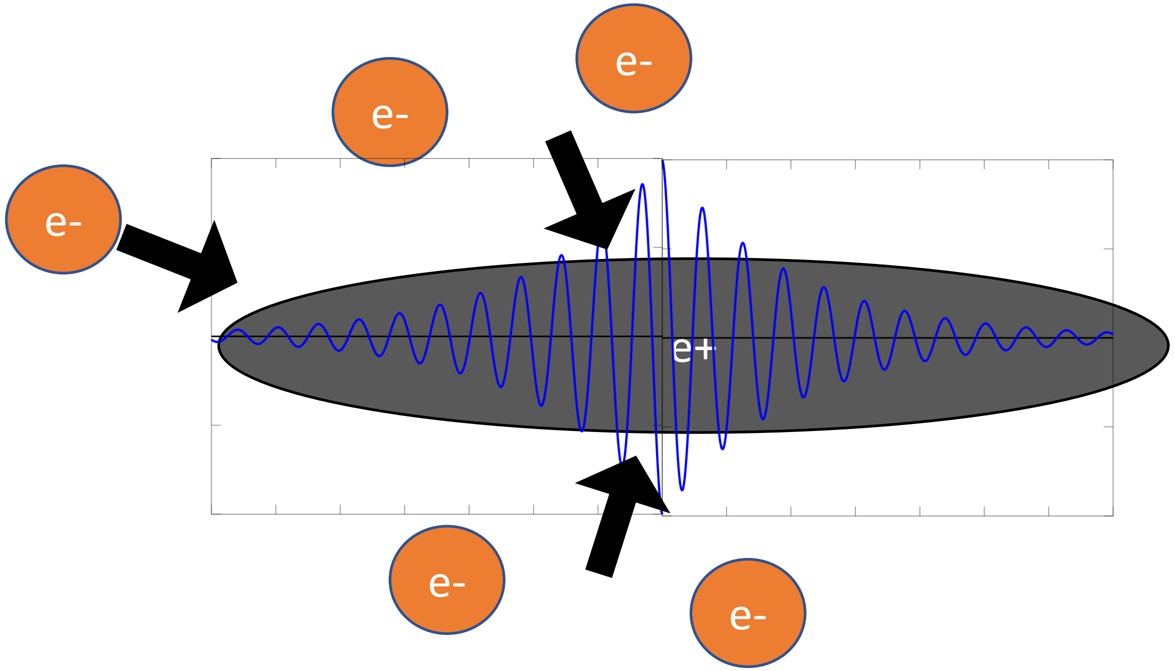
- ➢ Lower charge/efficiency
- ➢ Ultra-short bunches



| Beam | $k_b\sigma_z$ | $\sigma_{zt}$[um] | $\Delta\epsilon_N$[%] | Q [pC] | $\eta$[%] | $\delta, \delta_{tot}$ [%] |
|---|---|---|---|---|---|---|
| 1 | 0.78 | 5.2 | 5.5 | 0.75 | 1.7 | 0.4, 9.6 |
| 2 | 0.55 | 1.2 | 2.4 | 2.26 | 5.1 | 0.4, 2.3 |
| 3 | 0.35 | 0.24 | 0.4 | 4.50 | 9.6 | 0.9, 5.4 |
| 4 | 0.41 | 0.36 | 1.3 | 5.67 | 11.9 | 0.8, 6.1 |
| 5 | 0.35 | 0.24 | 1.7 | 8.50 | 17.0 | 1.3, 8.5 |

# Overcoming $k_b\sigma_z$ limitation?

- First, what is the physics behind the limitation? :

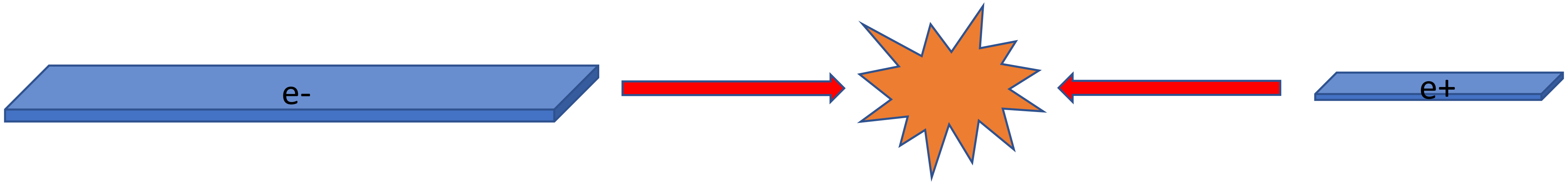


For higher $k_b\sigma_z$ tolerance: increase e- transverse momentum?

- warm plasma?
- Ion deficiency on axis?
- radial plasma e- ramp?

# Another direction: Asymmetric beam collisions

- What if we have asymmetric e-e+ collisions? Can we still achieve target lumi?



# e+ Regime Comparison Table

| | Finite Radius | Donut Driver | MNL | Linear | … |
|---|---|---|---|---|---|
| Plasma density [$cm^{-3}$] | 5E17 | 5E16 | 5E16 | 5E16 | |
| Init Energy [GeV] | 1 | 1 | 1 | 1 | |
| Charge | 50 pC | 100s pC - nC | ~10 pC | pC | |
| Ez [GeV/m] | 25-30 | 20-30 | ~5 | ~1 | |
| Efficiency | 2-3% | ~3-5% [up to 30%] | 10-25% | % level | |
| Uncorrelated Energy Spread | % level | 1-3% | % level | Sub-percent | |
| Total Energy Spread | ~5% w/o profile tailoring (sub-% w/) | 3-20% | 5-10% | % | |
| Emittance [um] | 0.1 | 1 | 2.5 | 0.5 | |
| Emittance Perservation | Yes [% level growth] | No [50% growth] | Yes [5-10% level growth] | Yes [% level growth] | |