中國科學院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

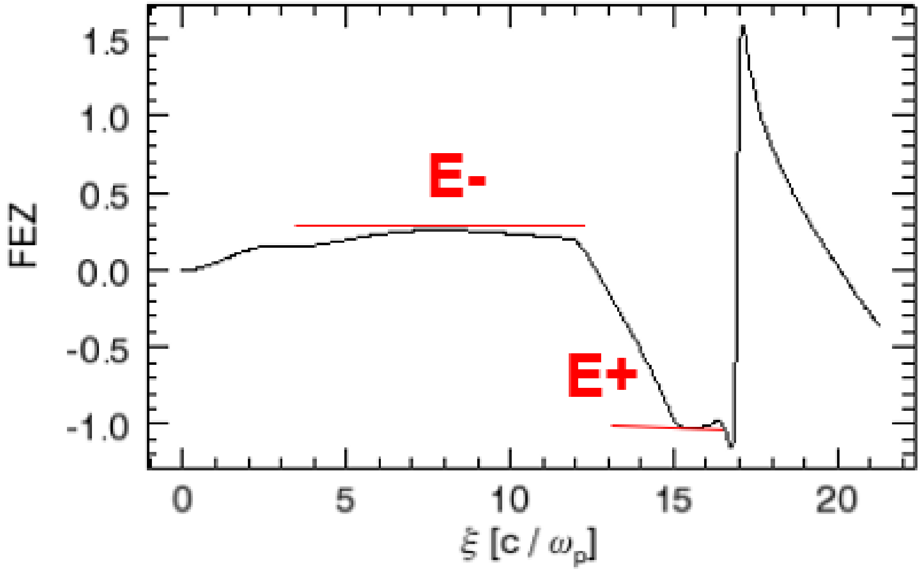
Recent Progress on CEPC Plasma Injector

Dr. Dazhang LI from AC, IHEP
on behalf of THU-IHEP AAC group

Outlines

- **Normal TR Scheme for e- acceleration**
- **Radiation reaction in a PWFA**
- **Optimal Beam loading in 2-bunch PWFA**
- **Scissor-cross ionization injection and laser interference triggered injection in LWFAs**

What is High Transformer Ratio?



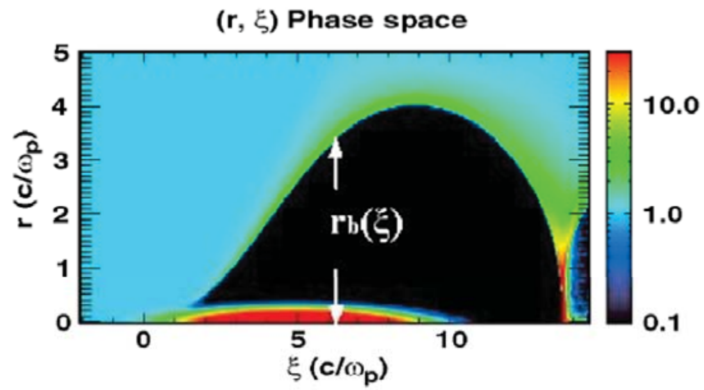
$$TR = E^{+}/E^{-}$$

$$TR = \frac{\bar{\gamma}_{trailer} - \gamma_{trailer\_initial}}{\bar{\gamma}_{driver} - \gamma_{driver\_initial}}$$

$$\eta = \frac{\sum_{i=1}^{n}{}_{E_i > E_t} (E_i - E_{trailer}) q_i}{\sum_{j=1}^{n}{}_{E_d > E_j} (E_{driver} - E_j) q_j}$$

Nonlinear(Bubble) regime: nb/np>>1 or $\Lambda = n_b/n_p k_p^2 \sigma_r^2 > 1$

HIGH TRANSFORMER RATIO



The equation of boundary: $r_b \frac{d^2 r_b}{d\xi^2} + 2\left[\frac{dr_b}{d\xi}\right]^2 + 1 = \frac{4\lambda(\xi)}{r_b^2}$

$$\psi(r_\perp, \xi) \approx \frac{r_b^2(\xi)}{4} - \frac{r^2}{4}$$

$$E_z = \frac{\partial}{\partial \xi}\psi(r_\perp, \xi) \simeq \frac{1}{2} r_b \frac{dr_b}{d\xi} \quad E_\perp = E_r - B_\theta = \frac{r}{2}$$

Lu W, Huang C, Zhou M, et al, PRL(2006)

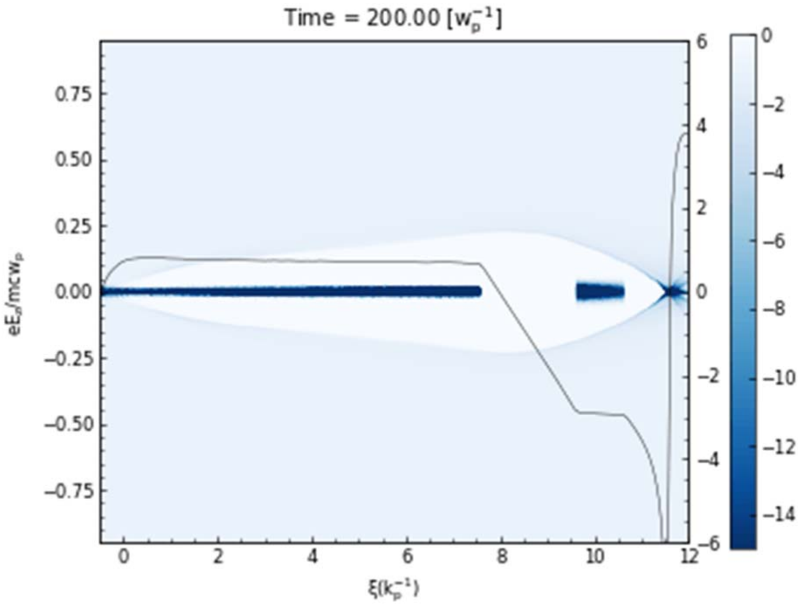
HTR mode, R ≥ (45.5-10)/10=3.55

Normal TR mode, R ≥ (20-10)/10=1

HTR e- Acceleration— ideal case

beam	Driver	Trailer
plasma density n_p $(\times 10^{16} cm^{-3})$	0.50334	
Driver energy E (GeV)	10	10
Normalized emittance $\epsilon_n(mm\ mrad)$	50→20	100
Length (um)	600	77
(matched) Spot size(um)	20→3.87	20→8.65
Charge (nC)	5.8	1→0.84
Energy spread δ_E $(\%)$	0	0
Beam distance (um)	149	

Accelerating distance (m)	10.65
Driver energy $E(GeV)$	1.30
Trailer energy $E(GeV)$	45.5
Normalized emittance $\epsilon_n(mm\ mrad)$	98.44
Charge(nc)	0.84 (0.78)
Energy spread $\delta_E(\%)$	0.56
TR	~ 4
Efficiency (%) (driver → trailer)	59.1



- **10 GeV → 45.5 GeV e- acc. (on paper) work**
- **Much smaller $\sigma_{x,y}$ → Increase Linac difficulty**
- **Trailer's charge close to minimum request**
- **Assuming fully symmetric drive beam!**

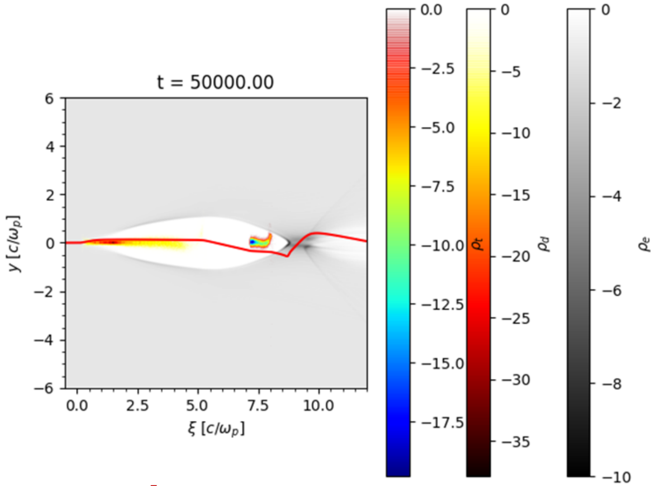
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

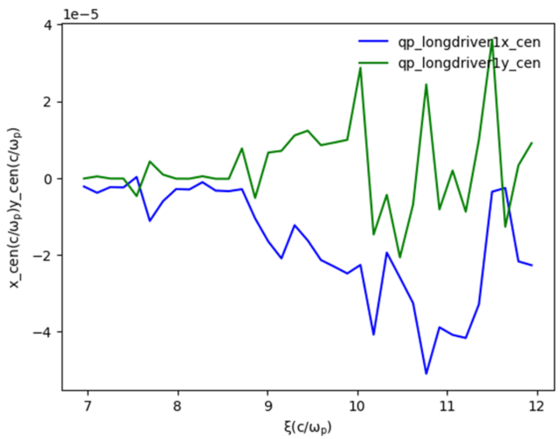
Error analysis → not fully symmetry

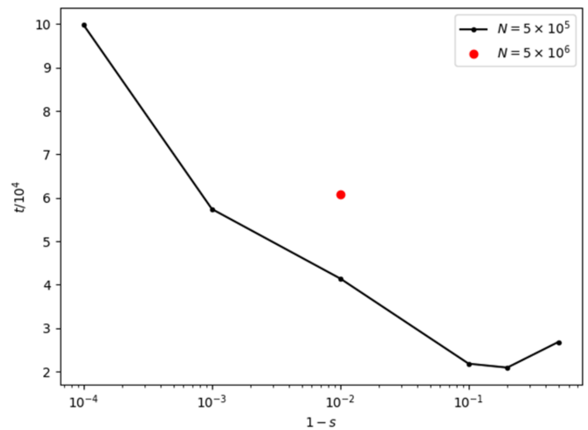
In the QuickPIC simulation, if the drive beam is not fully symmetry, even let $\langle x_d \rangle = 0$, the hosing instability occurs much earlier than we expect. For example, adding only **0.025nm** slice jitter to drive beam leads to severe hosing instability. Actually, the resolution of the simulation box is about 2 μm, which is much larger the added noise. **Is it physical or not?**

We did different studies and found that:

- Increase particle number → hosing improved
- Increase the jitter (noise) to dx level or larger → hosing became more serious
- Partial particles asymmetry → hosing improved



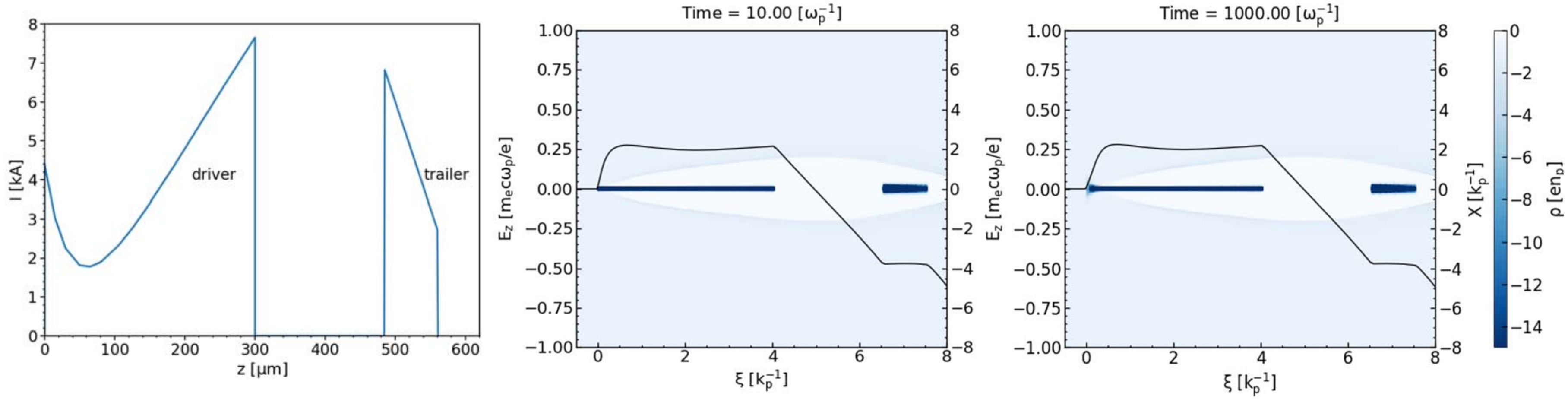




5×10^5 particles 99.99% symmetry $\sigma_z \sim 5$ lose 50% particles at 100000 ω_p^{-1}

Slide from Dr. X. N. Wang and Prof. W. M. An (2020); Dr. M. Zeng (2021)

Short driver for more stable acc.



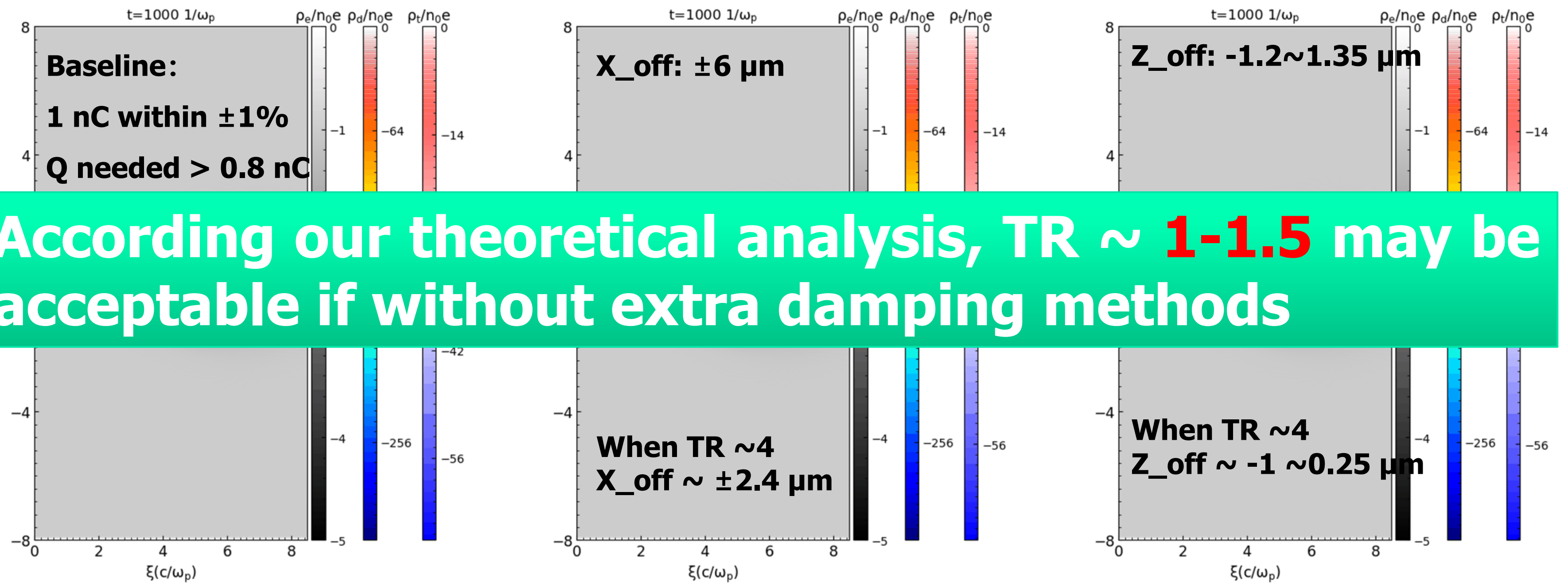
beam	Driver	Trailer
plasma density $n_p(\times 10^{16} cm^{-3})$	0.50334	
Driver energy $E(GeV)$	10	10
Normalized emittance $\epsilon_n(mm\ mrad)$	20	100
Length(um)	300	77
(matched)Spot size(um)	3.87	8.65
Charge(nC)	5.8→4	0.84→1.24
Energy spread $\delta_E(\%)$	0	0
Beam distance(um)	149→184	

	V1.0 HTR	V2.0 NTR
Accelerating distance (m)	10.7	4.8
Trailer energy $E(GeV)$	45.5	25
Normalized emittance $\epsilon_n(mm\ mrad)$	98.36	100
Charge(nC)	0.84	1.21
Energy spread $\delta_E(\%)$	0.40	0.40
TR	~ 4	~ 1.6
Efficiency(%) (driver -> trailer)	60.0	54.0

Slide from Dr. X. N. Wang, Dr. S. Y. Zhou and Prof. W. M. An (2021)

Backup scheme with TR ~ 1.5

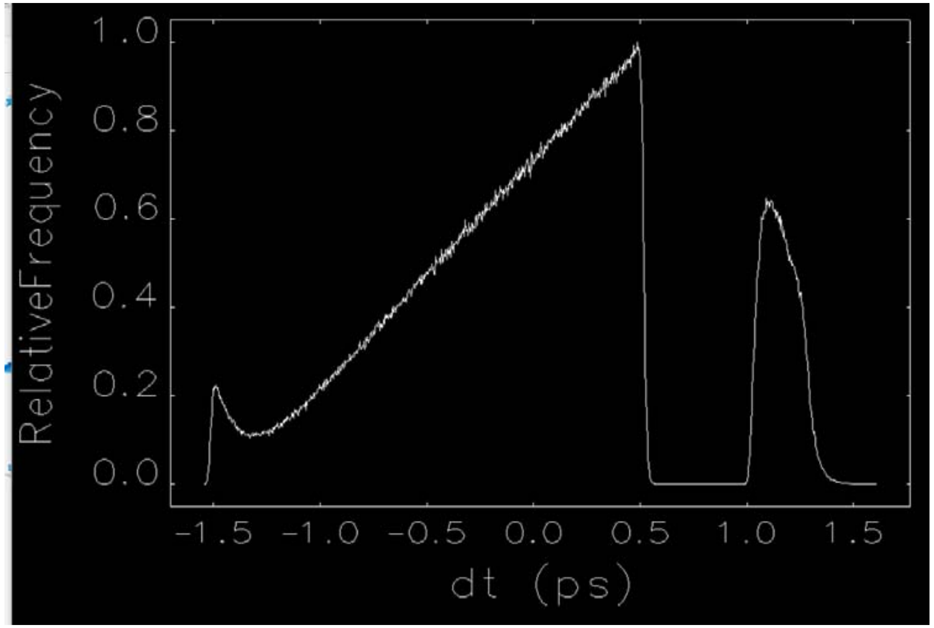
Asymmetry Ratio	Energy	Emittance (mm·mrad)	Bunch charge (0.2%)	Bunch charge (2%)	rms Energy spread
0	25.02 GeV	100 / 100	0.45 nC	1.36 nC	0.4%
0.1%	24.97 GeV	111 / 108	0.36 nC	1.36 nC	0.4%
1%	24.93 GeV	174 / 163	0.28 nC	1.36 nC	0.44%
2.5%	24.89 GeV	431 / 294	0.24 nC	1.33 nC	0.62%
10%	25.45 GeV	1057 / 1659	0.03 nC	0.28 nC	2.79%
2.5% (baseline)	26.25 GeV	645 / 496	1 nC (26.25 ±1%), TR ~ 1.76, η~52%		0.86%

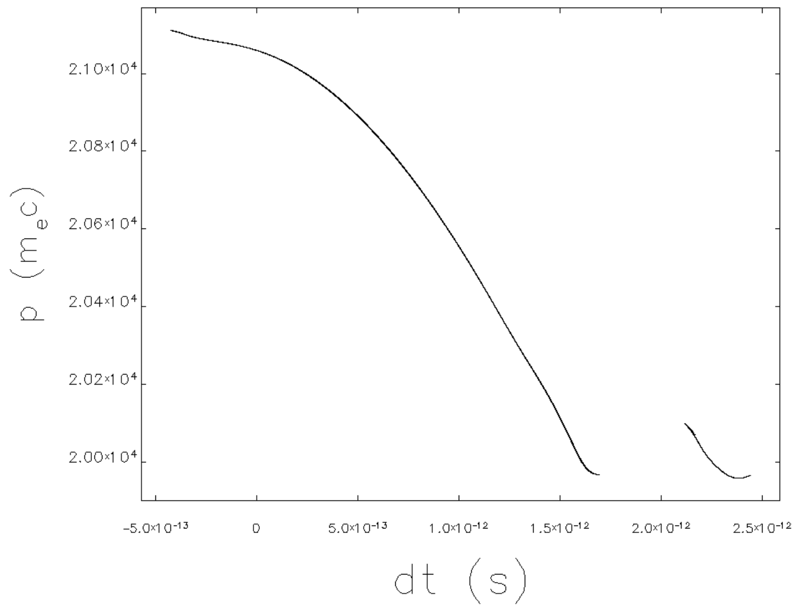


According our theoretical analysis, TR ~ 1-1.5 may be acceptable if without extra damping methods

Linac optimization for ideal beams

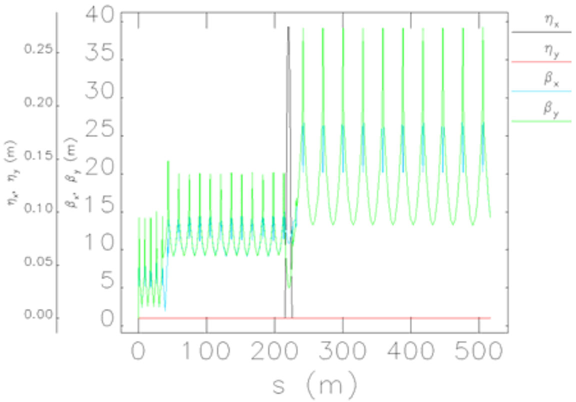
- Main Linac (Scheme-I)
  - If RF gun can provide electron beam with required shape, the main linac just accelerate beam to 10GeV.
  - Acceleration:
    - The longitudinal shape could be almost maintained
    - Short-range longitudinal wakefield + short bunch length + high bunch charge
      - Energy spread: 1.8% → Difficult design for FFS

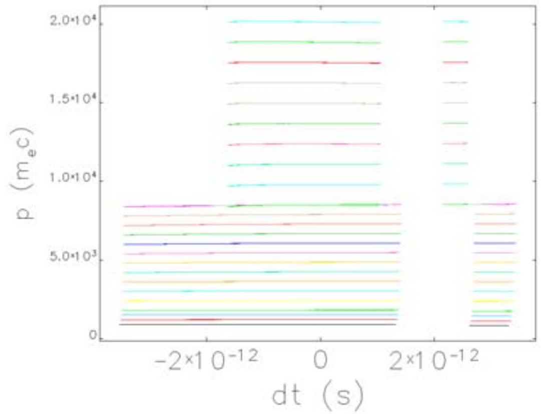


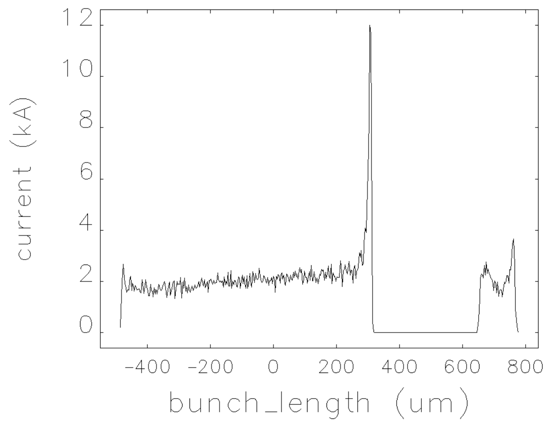


Linac optimization for ideal beams

- Main Linac (Scheme-II)
  - ✓ In order to decrease the energy spread and more flexible and compatible with other beam shaping scheme, one bunch compressor is introduced
    - Long bunch length beam + bunch compressor +short bunch length beam acceleration
    - High accelerating gradient s-band accelerating structure: 27MV/m
    - Energy spread: 0.275%
  - ✓ Longitudinal deformation, need more optimization







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Energy limit of a PWFA---not very low

IOP Publishing New J. Phys. 23 (2021) 075008 https://doi.org/10.1088/1367-2630/ac12fa

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

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OPEN ACCESS

RECEIVED
7 April 2021

REVISED
18 June 2021

ACCEPTED FOR PUBLICATION
9 July 2021

PUBLISHED
28 July 2021

PAPER

Radiation reaction of betatron oscillation in plasma wakefield accelerators

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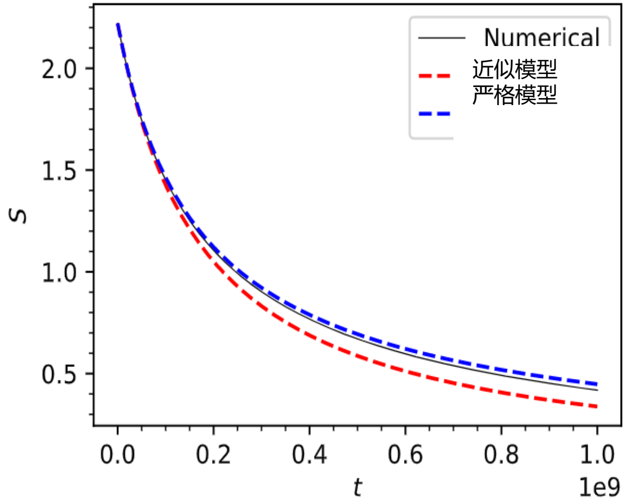

Table 1. Some examples of $\gamma_{0\max}$, L_S and $\chi_{\max}$ with varying n_p, S and γ_0.

Case No.	n_p (cm^{-3})	k_p (m^{-1})	S	$\gamma_{0\max}$	γ_0	L_S (m)	$\chi_{\max}$
1	10^{18}	1.88×10^5	2	5.4×10^6	1×10^5	563.2	1.9×10^{-4}
2					5×10^6	80.0	3.6×10^{-3}
3			8	2.1×10^6	1×10^5	140.8	3.9×10^{-4}
4					2×10^6	31.5	3.7×10^{-3}
5	10^{17}	5.95×10^4	2	1.2×10^7	1×10^5	5632	6.1×10^{-5}
6					1×10^7	563.2	1.9×10^{-3}
7			8	4.6×10^6	1×10^5	1408	1.2×10^{-4}
8					4×10^6	222.6	2.0×10^{-3}

- **Published on NJP (CAS, Q2 top)**
- **1st detailed analysis on RR effects of an e-'s BO in a PWA**
- **Both classical and quantum conditions are considered**
- **Can be ignored in CPI**

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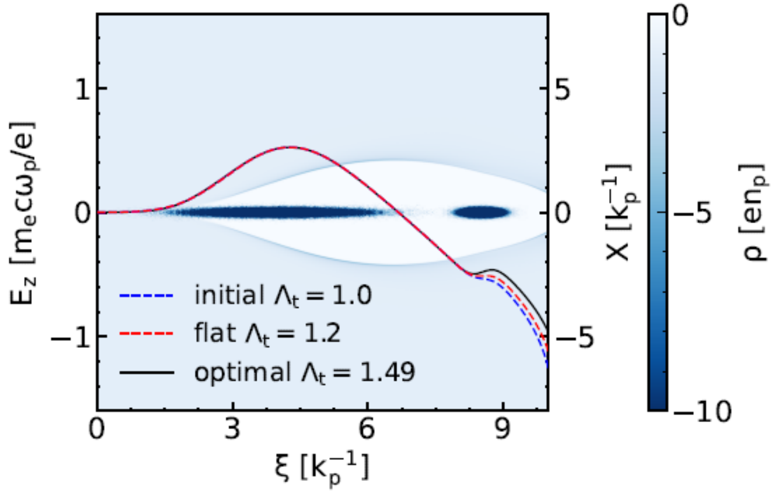
Try to find an optimal energy spread



- Trailer's relative energy spread is related to $Q_d, Q_t, \sigma_{zd}, \sigma_{zt}, \sigma_{rd}, \sigma_{rt}, d_{dt}, n_p$
- Reduce the coefficients' # by introducing charge per unit length $\Lambda = n_b \sigma_r^2$
- Scan a large range to fix the fitting formula for $\Lambda_t = f(\Lambda_d, \sigma_{zd}, \sigma_{zt}, d_{dt})$

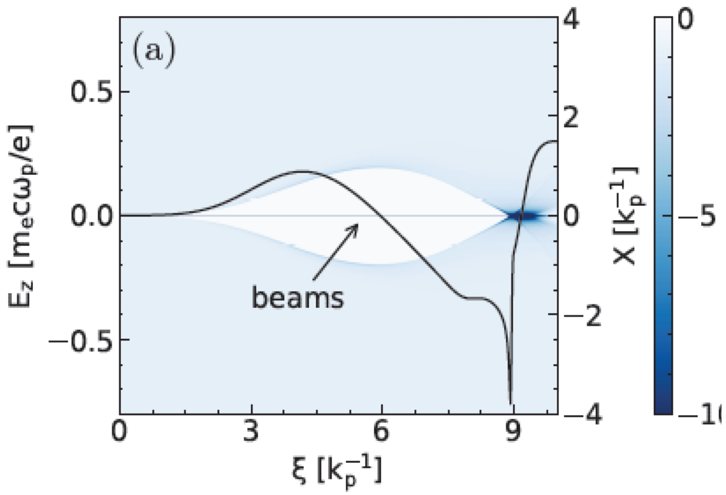


TABLE I. Parameters range obtained from automatic optimizations.

Parameters	Range
Λ_d	[0.0885, 7.70]
σ_{zd} [k_p^{-1}]	[0.0952, 1.90]
d_{dt} [k_p^{-1}]	[1.60, 11.1] (the gloabal range)
σ_{zt} [k_p^{-1}]	[0.0952, 0.857]
Λ_t	[0.0627, 3.14]

Fitting formula for Λ_t and R

$$\Lambda_t = h_0 + h_1\Lambda_d + h_2\sigma_{zd} + h_3\sigma_{zt} + h_4 d_{dt} + h_5\Lambda_d^2 + h_6\Lambda_d\sigma_{zd} + h_7\Lambda_d\sigma_{zt} + h_8\Lambda_d d_{dt}$$
$$+ h_9\sigma_{zd}^2 + +h_{10}\sigma_{zd}\sigma_{zt} + h_{11}\sigma_{zd}d_{dt} + h_{12}\sigma_{zt}^2 + h_{13}\sigma_{zt}d_{dt} + h_{14}d_{dt}^2 + h_{15}\Lambda_d^3 + h_{16}\Lambda_d^2\sigma_{zd}$$
$$+ h_{17}\Lambda_d^2\sigma_{zt} + h_{18}\Lambda_d^2 d_{dt} + h_{19}\Lambda_d\sigma_{zd}^2 + h_{20}\Lambda_d\sigma_{zd}\sigma_{zt} + h_{21}\Lambda_d\sigma_{zd}d_{dt} + h_{22}\Lambda_d\sigma_{zt}^2 \qquad (2)$$
$$+ h_{23}\Lambda_d\sigma_{zt}d_{dt} + h_{24}\Lambda_d d_{dt}^2 + h_{25}\sigma_{zd}^3 + h_{26}\sigma_{zd}^2\sigma_{zt} + h_{27}\sigma_{zd}^2 d_{dt} + h_{28}\sigma_{zd}\sigma_{zt}^2$$
$$+ h_{29}\sigma_{zd}\sigma_{zt}d_{dt} + h_{30}\sigma_{zd}d_{dt}^2 + h_{31}\sigma_{zt}^3 + h_{32}\sigma_{zt}^2 d_{dt} + h_{33}\sigma_{zt}d_{dt}^2 + h_{34}d_{dt}^3,$$

h_1=3.658×10^{-1}	h_2=9.119×10^{-1}	h_3=-1.083	h_4=3.062×10^{-1}	h_5=-3.754×10^{-2}
h_6=2.344	h_7=1.281×10^{-1}	h_8=-5.028×10^{-2}	h_9=-7.136×10^{-1}	h_{10}=-1.915×10^{-1}
h_{11}=-1.316×10^{-1}	h_{12}=-2.167	h_{13}=1.034	h_{14}=-7.607×10^{-2}	h_{15}=-2.391×10^{-3}
h_{16}=-7.570×10^{-2}	h_{17}=2.641×10^{-2}	h_{18}=1.160×10^{-2}	h_{19}=-8.626×10^{-1}	h_{20}=-2.424×10^{-1}
h_{21}=9.630×10^{-2}	h_{22}=3.874×10^{-1}	h_{23}=-7.137×10^{-2}	h_{24}=-3.061×10^{-3}	h_{25}=1.238×10^{-1}
h_{26}=3.752×10^{-2}	h_{27}=7.655×10^{-2}	h_{28}=5.197×10^{-1}	h_{29}=-2.585×10^{-2}	h_{30}=-6.071×10^{-3}
h_{31}=-2.866	h_{32}=1.231	h_{33}=-2.525×10^{-1}	h_{34}=6.674×10^{-3}	h_0=-5.014×10^{-1}

- **By using the BFGS algorithm and QuickPIC to obtain a large amount of optimal cases**
- **By using polynomial regression to calculate all the coefficients**
- **Valid for 2-bunch, tri-Gaussian electron beams**
- **Plan to submit to NJP**

$$R = p_0 + p_1\Lambda_d + p_2\sigma_{zd} + p_3\sigma_{zt} + p_4 d_{dt} + p_5\Lambda_t + p_6\Lambda_d^2 + p_7\Lambda_d\sigma_{zd} + p_8\Lambda_d\sigma_{zt}$$
$$+ p_9\Lambda_d d_{dt} + p_{10}\Lambda_d\Lambda_t + p_{11}\sigma_{zd}^2 + p_{12}\sigma_{zd}\sigma_{zt} + p_{13}\sigma_{zd}d_{dt} + p_{14}\sigma_{zd}\Lambda_t \qquad (3)$$
$$+ p_{15}\sigma_{zt}^2 + p_{16}\sigma_{zt}d_{dt} + p_{17}\sigma_{zt}\Lambda_t + p_{18}d_{dt}^2 + p_{19}d_{dt}\Lambda_t + p_{20}\Lambda_t^2,$$

p_1=0.3199	p_2=0.3178	p_3=0.3084	p_4=0.7241	p_5=-0.8454	p_6=0.02719	p_7=0.4858
p_8=0.4140	p_9=-0.1070	p_{10}=-0.02761	p_{11}=-0.2779	p_{12}=-0.4929	p_{13}=0.2440	p_{14}=-0.3681
p_{15}=1.632	p_{16}=-0.6407	p_{17}=-0.01004	p_{18}=-0.01716	p_{19}=0.01430	p_{20}=0.1439	p_0=-1.453

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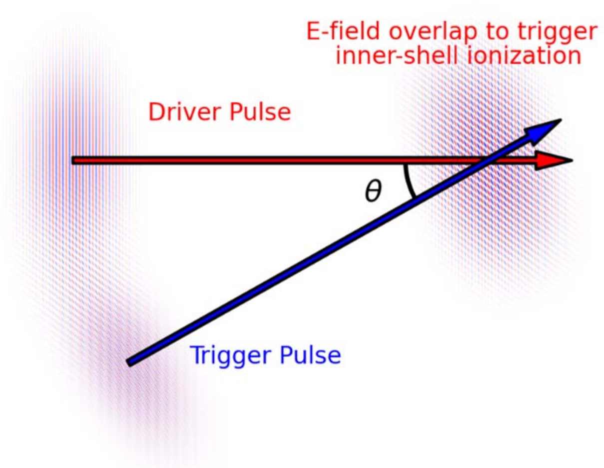
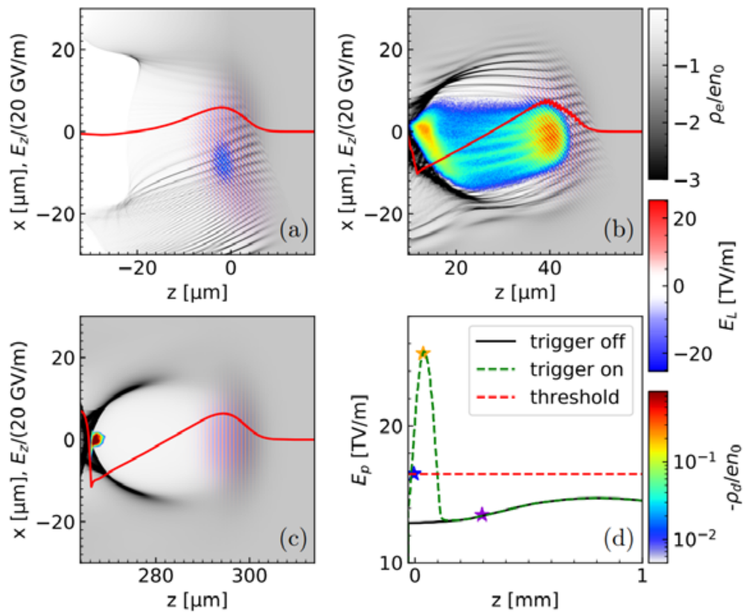
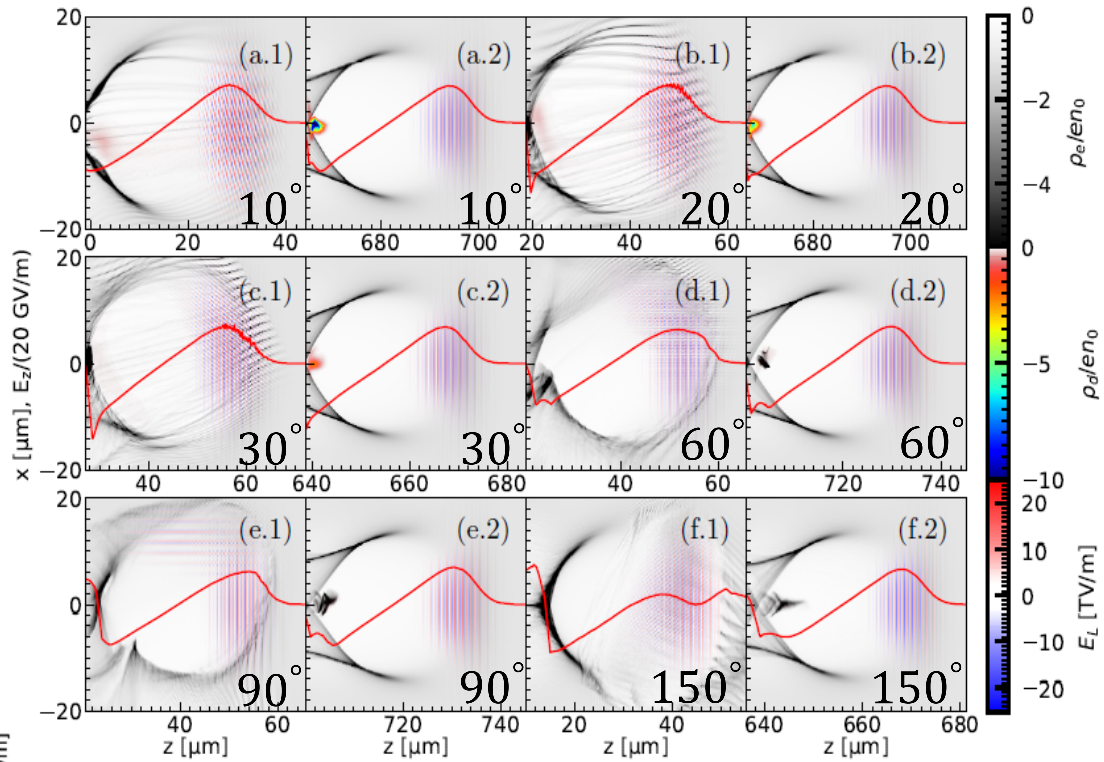
Scissor-cross ionization injection

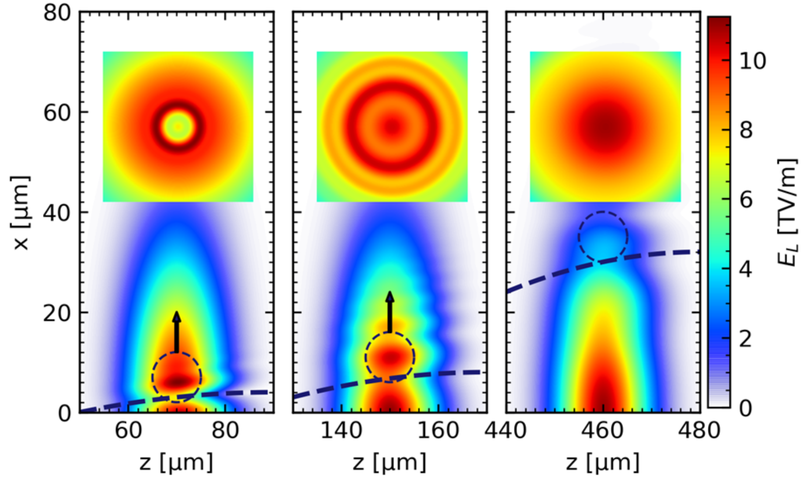


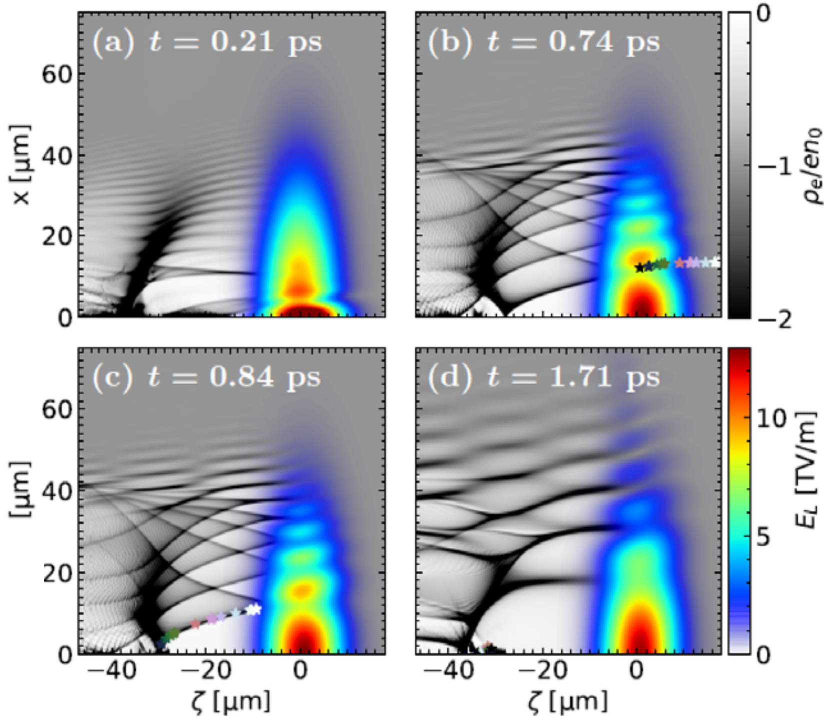


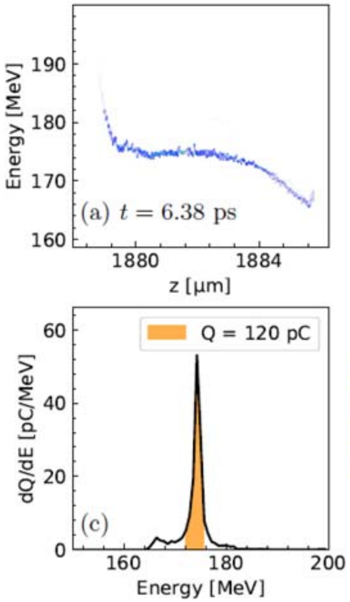


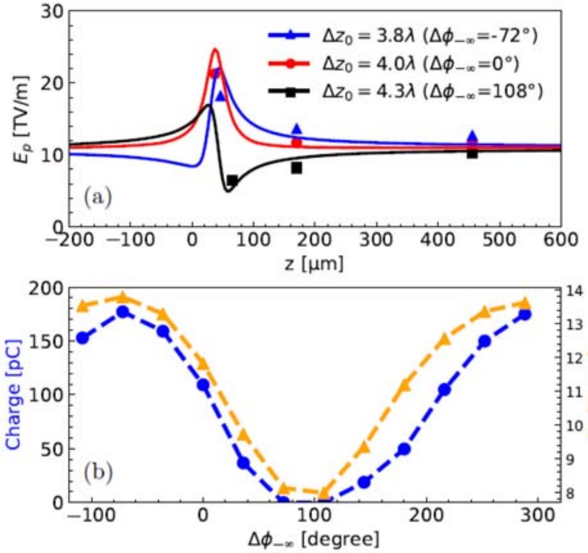
- **In 3D simulation, 100 TW (800nm) + 25 TW (400 nm) @ 8° (should not be the optimized condition), ~ 500 MeV, 40 pC, 1%**
- **In 2D simulation, ΔE/E ~ 0.7% @ ~ 580 MeV**
- **Accepted by PPCF (CAS Q2)**

Improved injection via bubble evolving









- In simulation, with 230 TW laser, we can get ~ 750 MeV, 130 pC, 0.4% e- beam
- Sensitive to 2-laser time delay (sub fs)
- Propose an realistic experiment @ Huairou
- Manuscript V1.0 is done

Summary and prospects

- **Normal transformer ratio electron acceleration**
  - TR ~ 1.5 is much more stable than TR ~ 4. Question: 10→20 or 20→45?
  - Start-to-end simulation is ongoing, together with detailed tolerance analysis
  - There are powerful damping mechanisms in a real PWFA. HTR is still alive
- **Radiation reaction effects in PWFA is studied**
  - So far, it's completely safe for CEPC plasma injector.
  - Can not be ignored for future very high energy PWFA colliders
- **2-bunch PWFA optimal method is studied**
  - 2 fitting formulas are given. It's important to design a PWFA
- **Some studies on controlled injection in LWFA are presented**

Thank you!