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

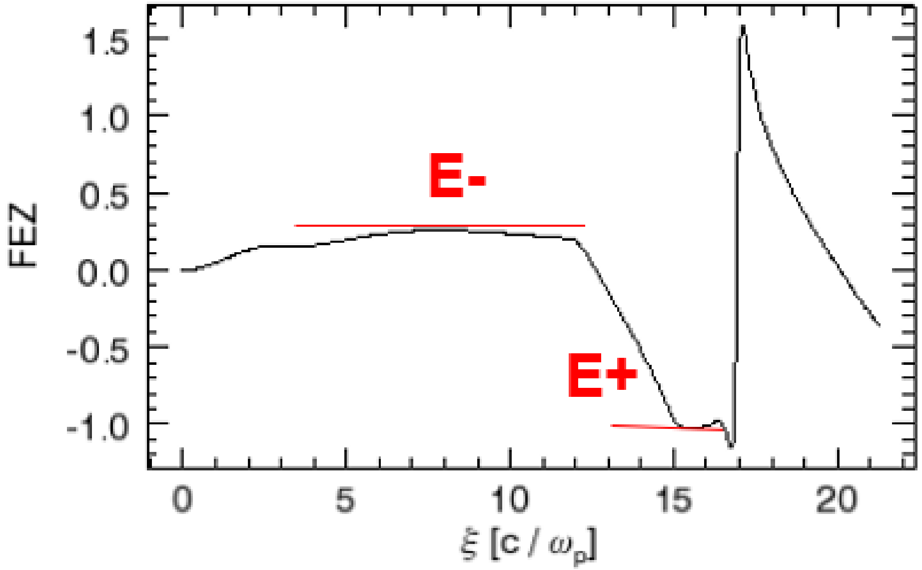
Recent Progress on CEPC Plasma Injector

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?



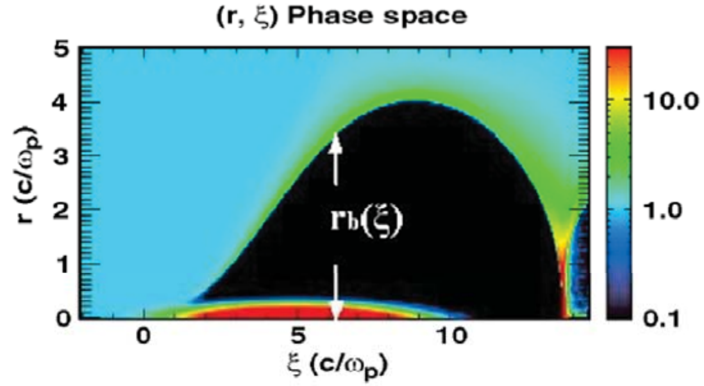
$$TR = E^{+}/E^{-}$$

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

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

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)

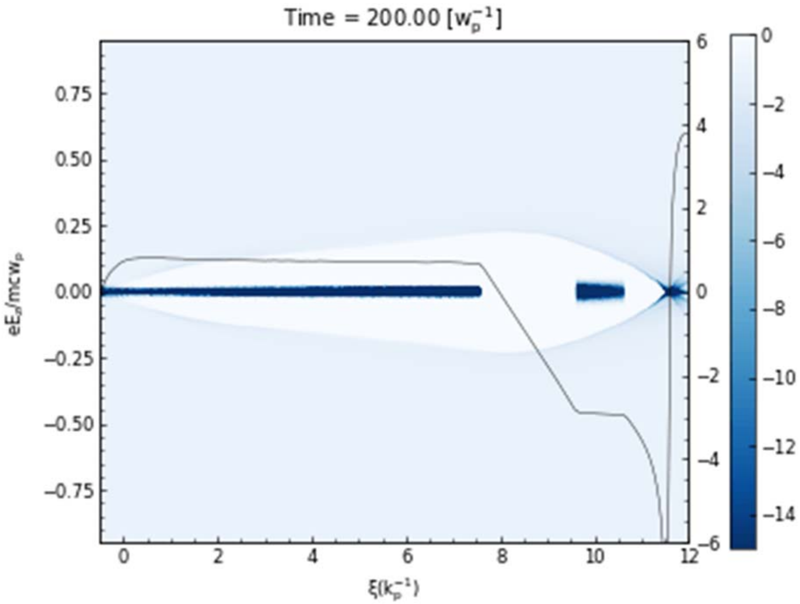
HTR mode, R ≥ (45.5-10)/10=3.55

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!**

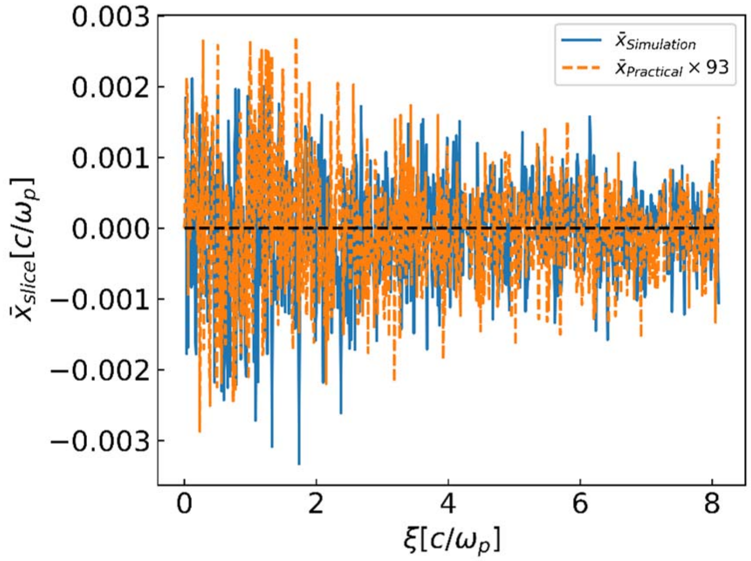
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

Initial noise macro vs. practical

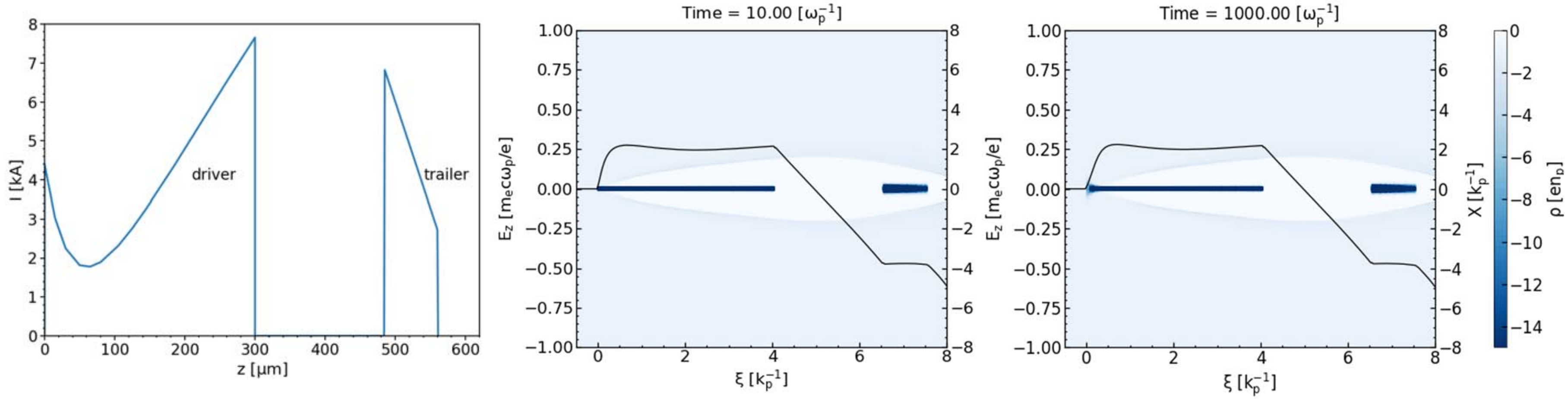
- An important question is "How do the beams evolve from their initial statistical noise?"
- Another question is "Does the hosing instability set any limit on the transformer ratio of PWFA?"

Initial noise of a collimated beam

- Particle number is N, transverse profile is Gaussian with r.m.s. size σ_r $\rightarrow$ the jitter of bunch center obeys a Gaussian distribution $N(0,\ \sigma_r/\sqrt{N})$
- For PIC simulation, number of macro particle is much less than practical particle number, so the initial noise level is different in magnitudes.
- For a 5.8nC driver, the particle number in QuickPIC is $128 \times 128 \times 256$, which is $1/93^2$ of the practical particle number.
- Assuming the real condition is similar with the simulation with the asymmetry ratio ~ $1/\sqrt{N}$



Short driver for more stable acc.



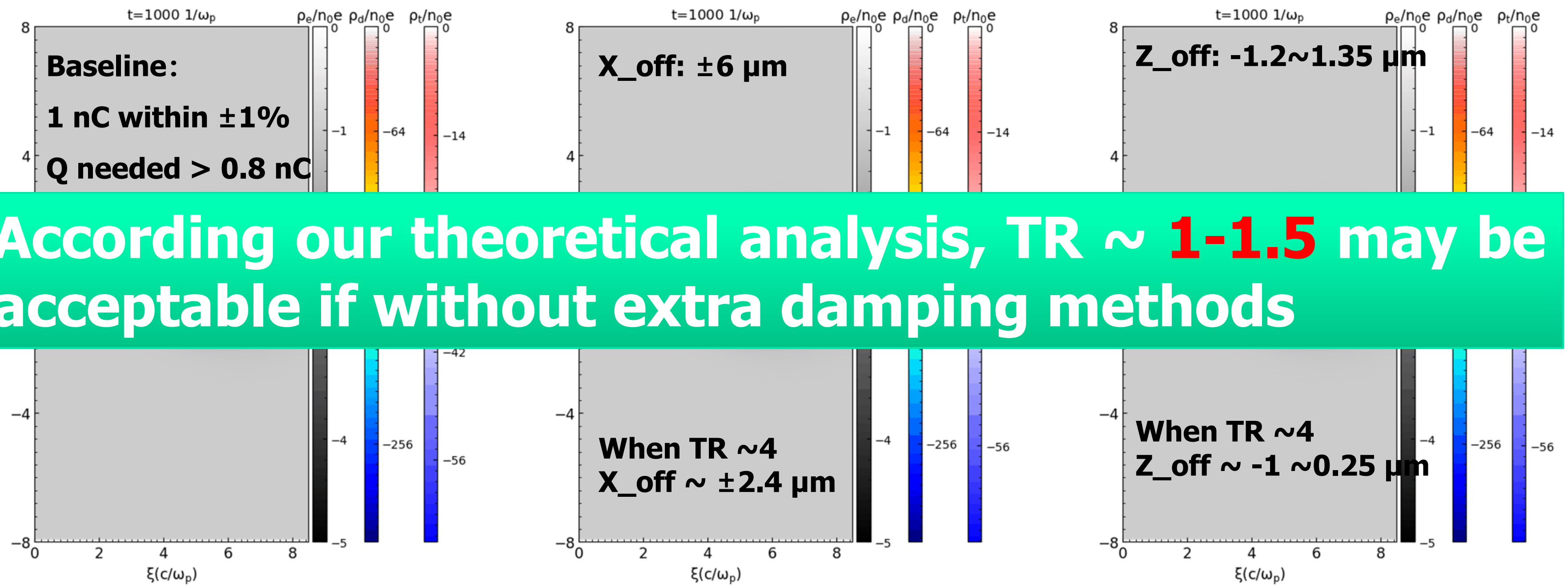
beam	Driver	Trailer
plasma density $n_p (\times 10^{16} cm^{-3})$	0.50334	
Driver energy $E(GeV)$	10	10
Normalized emittance $\epsilon_n (mm\ mrad)$	20	100
Length(um)	600→300	77
(matched)Spot size(um)	3.87	8.65
Charge(nC)	5.8→4	0.84→1.36
Energy spread $\delta_E (\%)$	0	0
Beam distance(um)	149→184	

	V1.0 HTR	V2.0 NTR
Accelerating distance (m)	10.7 (16w dt)	4.86 (7.2w dt)
Trailer energy $E(GeV)$	45.5	25
Normalized emittance $\epsilon_n (mm\ mrad)$	98.36	100
Charge(nC)	0.84	1.36
Energy spread $\delta_E (\%)$	0.40	0.37
TR	~ 4	~ 1.6
Efficiency(%) (driver -> trailer)	60.0	56.8

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

Backup scheme with TR ~ 1.5

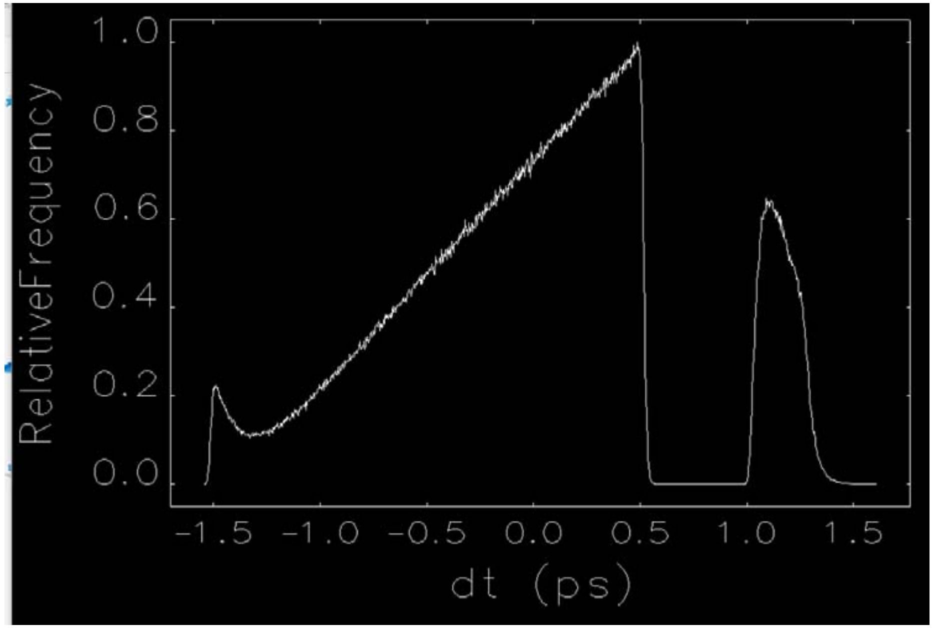
Asymmetry Ratio	Energy	Emittance (mm·mrad)	Bunch charge (0.2%)	Bunch charge (2%)	rms Energy spread
0	25.02 GeV	100 / 100	0.45 nC	1.36 nC	0.4%
0.1%	24.97 GeV	111 / 108	0.36 nC	1.36 nC	0.4%
1%	24.93 GeV	174 / 163	0.28 nC	1.36 nC	0.44%
2.5%	24.89 GeV	431 / 294	0.24 nC	1.33 nC	0.62%
10%	25.45 GeV	1057 / 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%

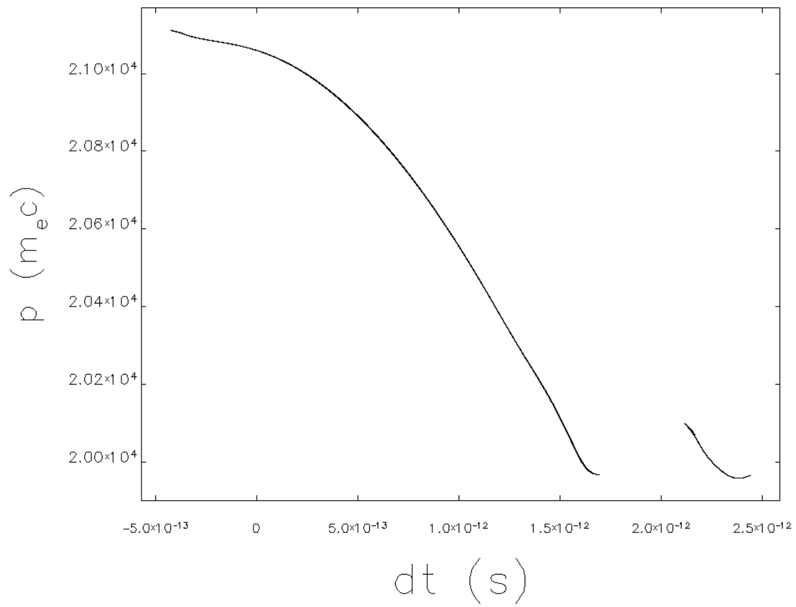


According our theoretical analysis, TR ~ 1-1.5 may be acceptable if without extra damping methods

Linac optimization for ideal beams

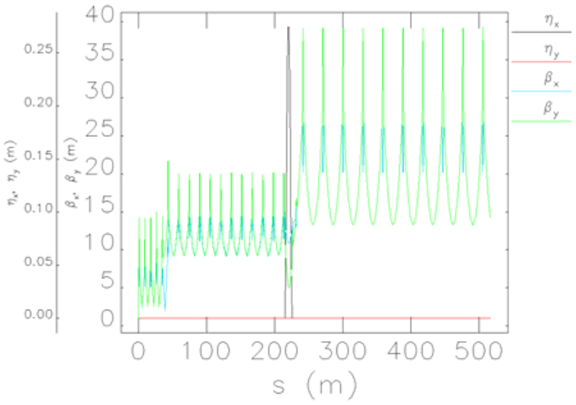
- Main Linac (Scheme-I)
  - ✓ If RF gun can provide electron beam with required shape, the main linac just accelerate beam to 10GeV.
  - ✓ Acceleration:
    - The longitudinal shape could be almost maintained
    - Short-range longitudinal wakefield + short bunch length + high bunch charge
      - Energy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

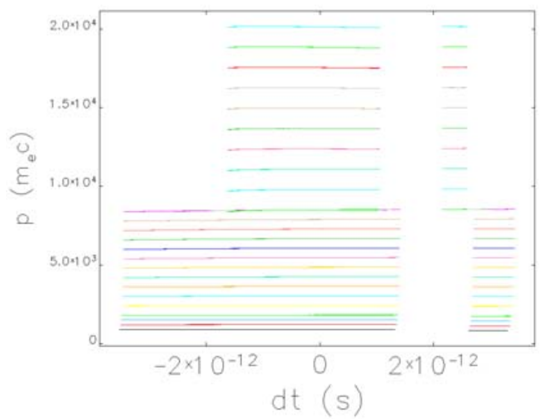


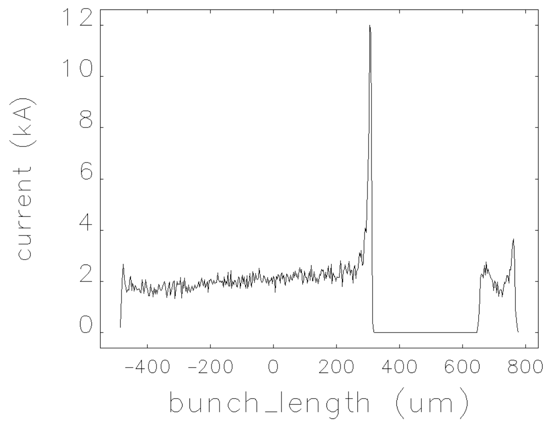


Linac optimization for ideal beams

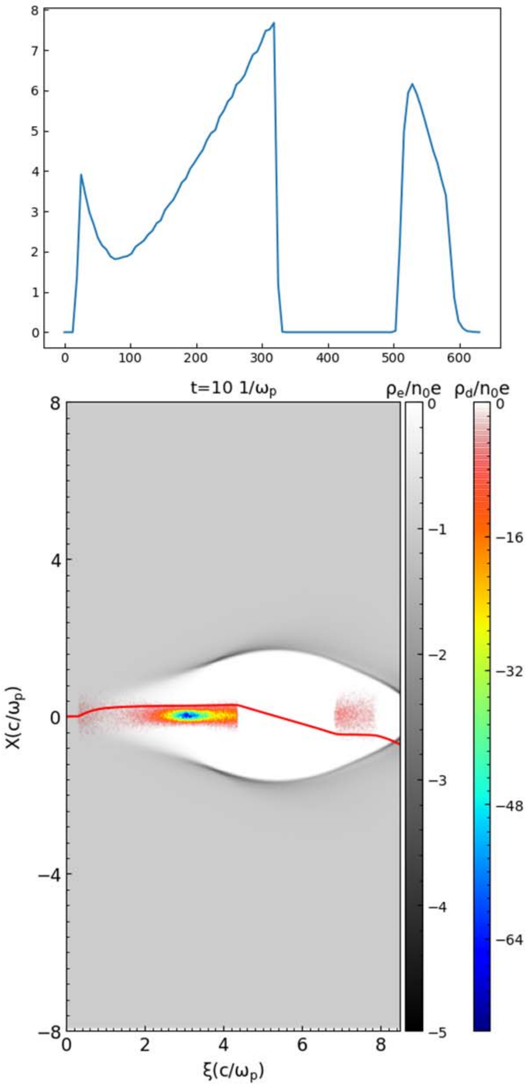
- Main Linac (Scheme-II)
  - ✓ In order to decrease the energy spread and more flexible and compatible with other beam shaping scheme, one bunch compressor is introduced
    - Long bunch length beam + bunch compressor +short bunch length beam acceleration
    - High accelerating gradient s-band accelerating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

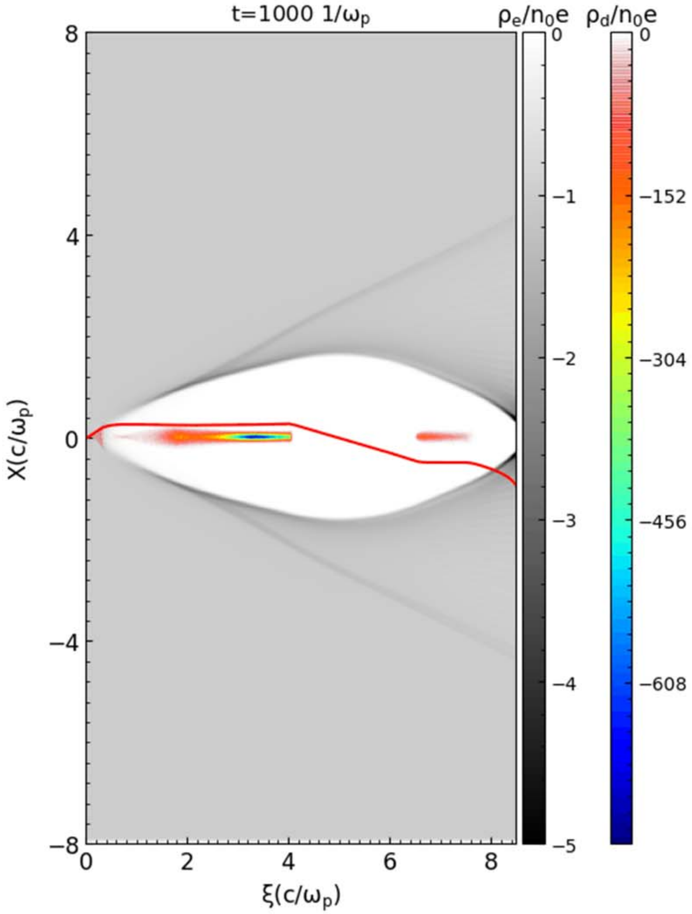






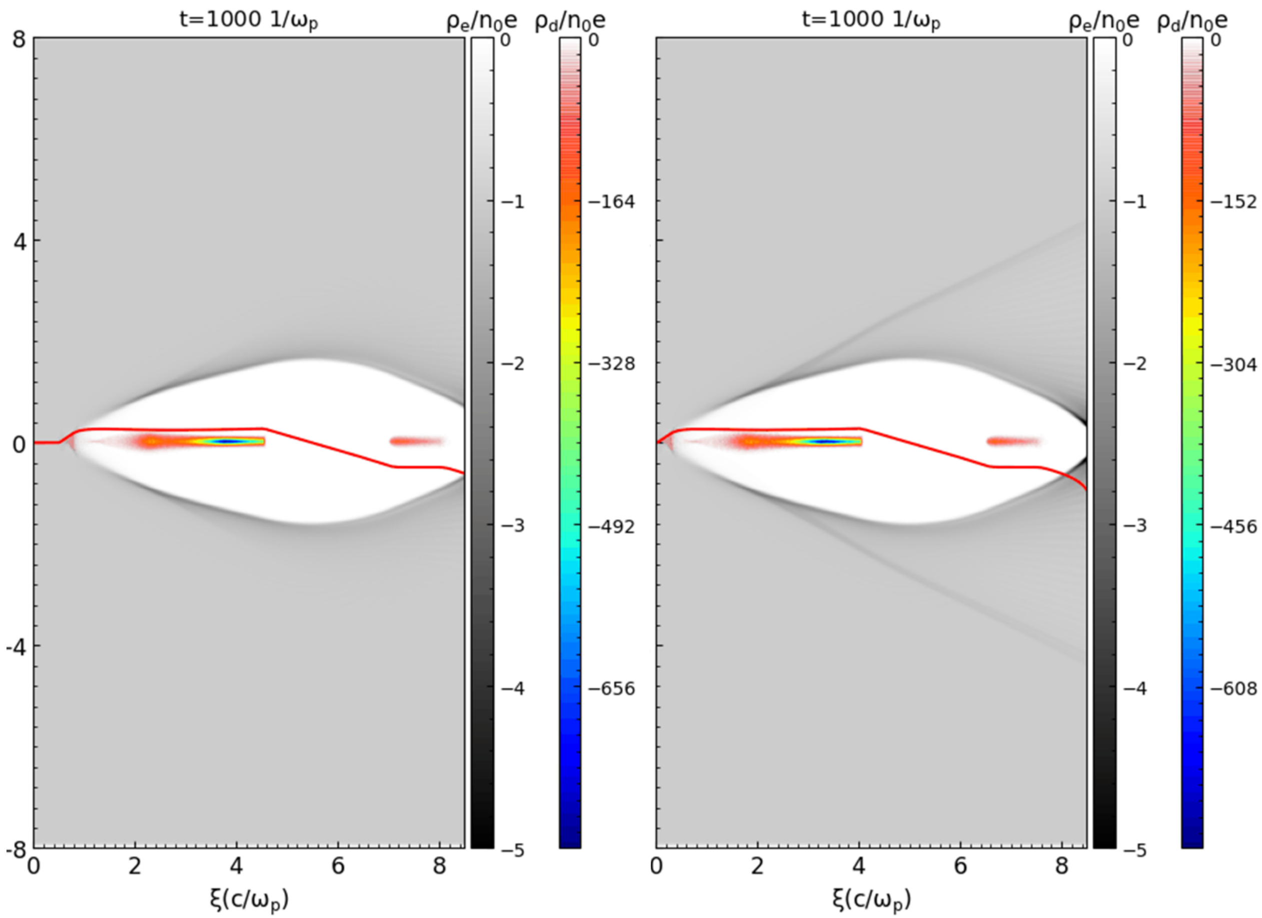
Start-to-end simulation (linac → CPI)





- **Driver:**
  - **<x>=11.63 μm → 3.64 μm**
  - **<y>=20.13 μm → 3.64 μm**
- **Trailer:**
  - **<x>=20.52 μm → 8.65 μm**
  - **<y>=35.06 μm → 8.65 μm**
- **Total particle # ~ 1e6**
- **Real particle # ~ 2.5e10**
- **Beam loss starts around 25000dt. Only 7.6 pC particle (E ≥ 20 GeV) left after 72000dt acceleration**

Start-to-end simulation (linac → CPI)



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  - **<y>=35.06 μm → 8.65 μm**
- **Total particle # ~ 1e6**
- **Real particle # ~ 2.5e10**
- **99% symmetry, without plasma matching section**
  - **<E>=26.9 GeV**
  - **σ_δ=1.46%**
  - **Q=1.27 nC (> 1nC/1%bw)**
- **Non-ideal energy chirper**

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Energy limit of a PWFA---not very low

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Radiation reaction of betatron oscillation in plasma wakefield accelerators

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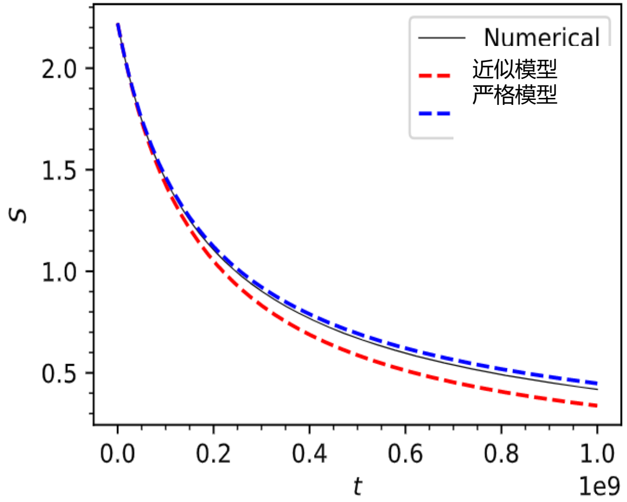

Table 1. Some examples of $\gamma_{0\max}$, L_S and $\chi_{\max}$ with varying n_p, S and γ_0.

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}

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

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Try to find an optimal energy spread

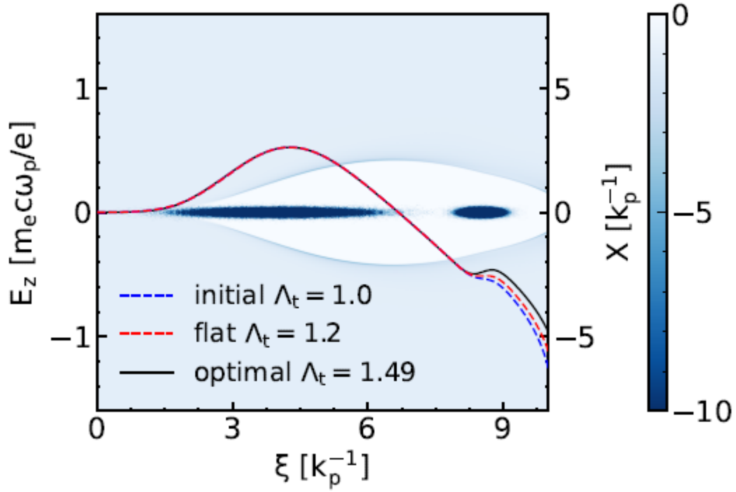
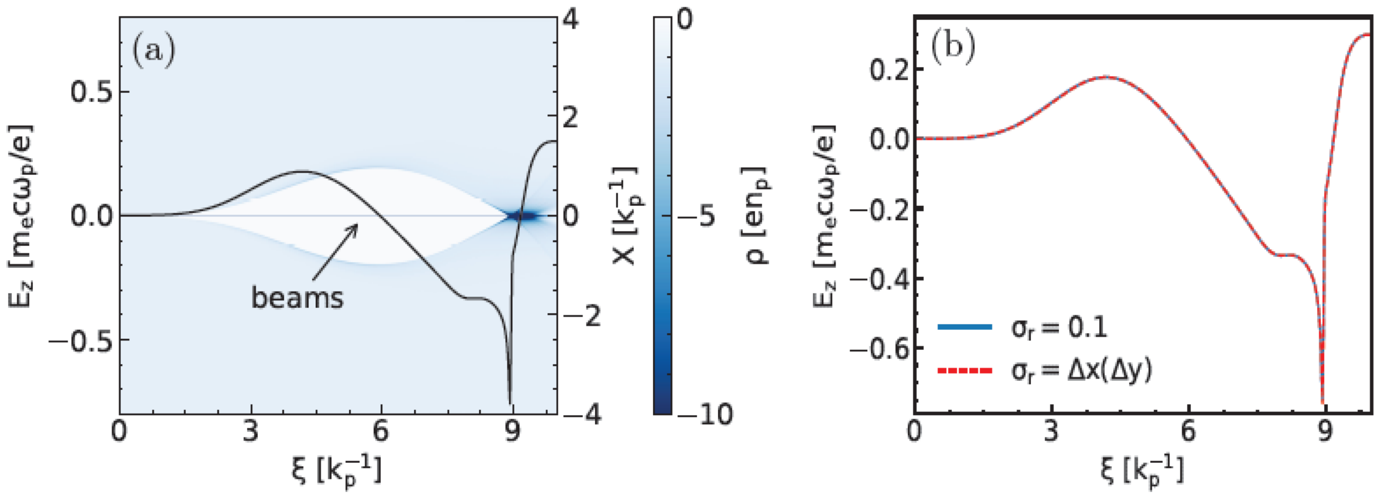


TABLE I. Parameters range obtained from automatic optimizations.

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	$[0.0627, 3.14]$

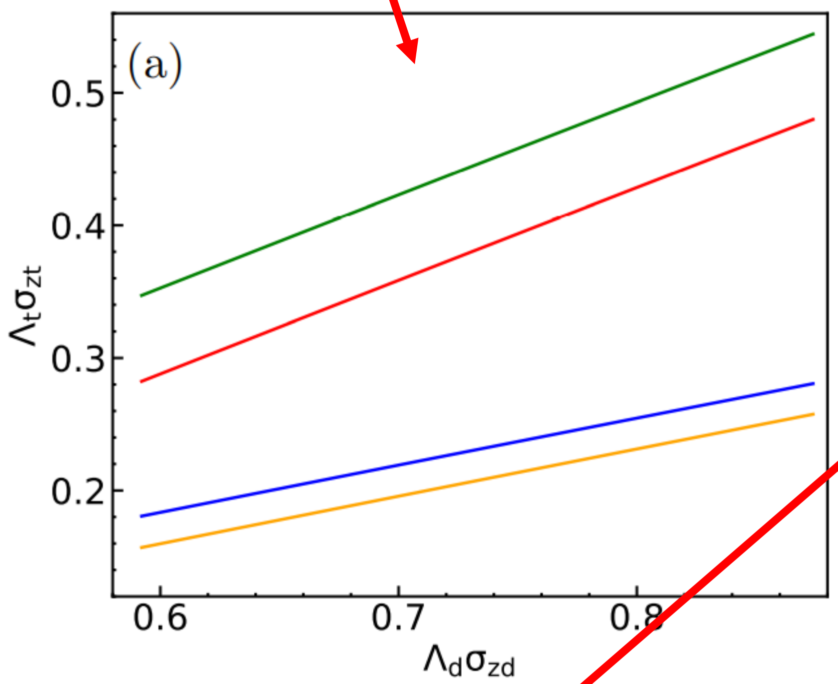


Fitting formula for Λ_t and R

- By using the BFGS algorithm and QuickPIC to obtain a large amount of optimal cases
- By using polynomial regression together with k-fold cross-validation method to determine the degree and calculate all the coefficients
- Valid for 2-bunch, tri-Gaussian electron beams, could be extended to other beam longitudinal profile
- **Submitted to PPCF, under peer review** http://arxiv.org/abs/2202.07401

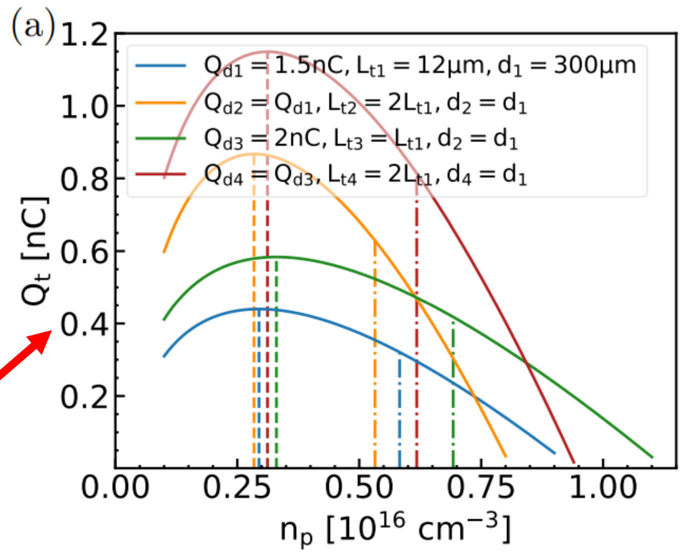
Some simplified applications

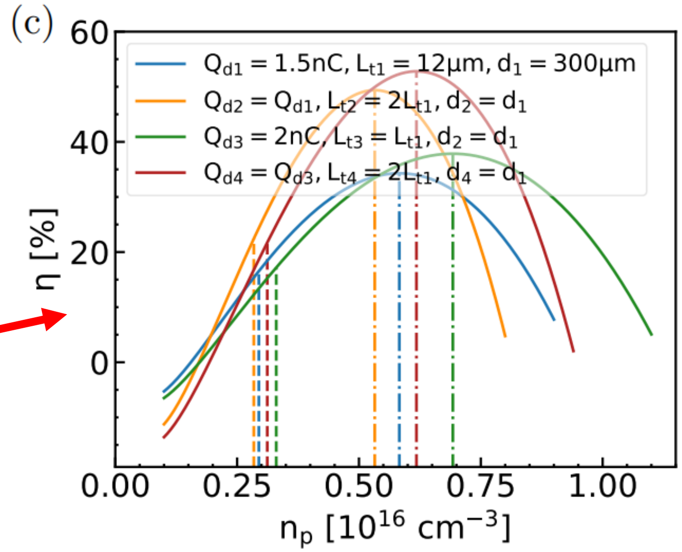
$$\Lambda_t\sigma_{zt} = A\cdot(\Lambda_d\sigma_{zd})^3 + B\cdot(\Lambda_d\sigma_{zd})^2 + D\cdot(\Lambda_d\sigma_{zd}) + G,$$



$$Q_t[\mathrm{nC}] = H\cdot n_p^{\frac{3}{2}}[10^{16}\mathrm{cm}^{-3}] + M\cdot n_p[10^{16}\mathrm{cm}^{-3}] + P\cdot n_p^{\frac{1}{2}}[10^{16}\mathrm{cm}^{-3}] + S$$

$$\eta = \frac{Q_t[\mathrm{nC}]}{Q_d[\mathrm{nC}]}\cdot R = \frac{X_1 n_p^{\frac{9}{2}} + X_2 n_p^4 + X_3 n_p^{\frac{7}{2}} + X_4 n_p^3 + X_5 n_p^{\frac{5}{2}} + X_6 n_p^2 + X_7 n_p^{\frac{3}{2}} + X_8 n_p + X_9 n_p^{\frac{1}{2}} + X_{10}}{Q_d[\mathrm{nC}]}$$





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Scissor-cross ionization injection

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Scissor-cross ionization injection in laser wakefield accelerators

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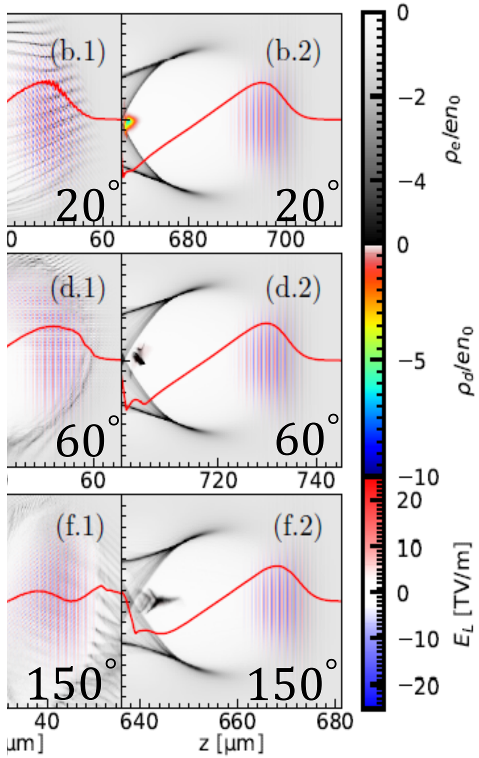
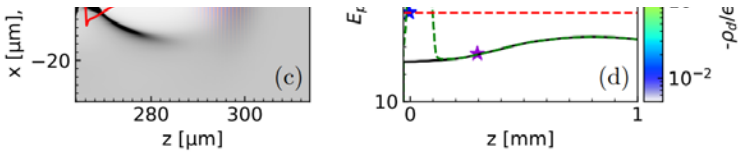
Abstract
We propose to use a frequency-doubled pulse colliding with the driving pulse at an acute angle to trigger ionization injection in a laser wakefield accelerator. This scheme effectively reduces the duration of the injection; thus, high injection quality is obtained. Three-dimensional particle-in-cell simulations show that electron beams with energy of ∼500 MeV, a charge of ∼40 pC, energy spread of ∼1% and normalized emittance of a few millimeter milliradian can be produced by ∼100 TW laser pulses. By adjusting the angle between the two pulses, the intensity of the trigger pulse and the gas doping ratio, the charge and energy spread of the electron beam can be controlled.



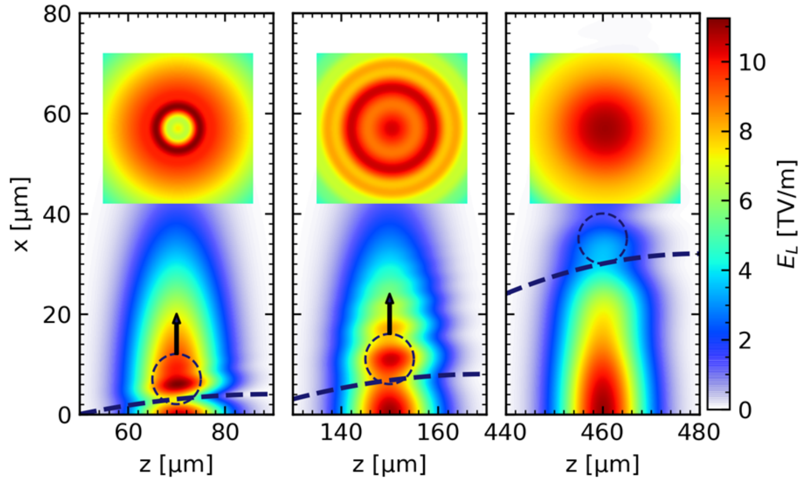
TW (800nm) + 25 TW

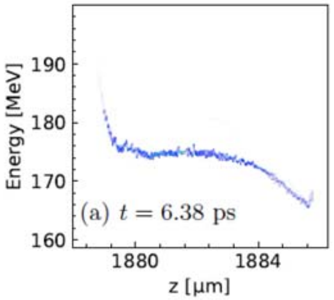
MeV, 40 pC, 1% (could

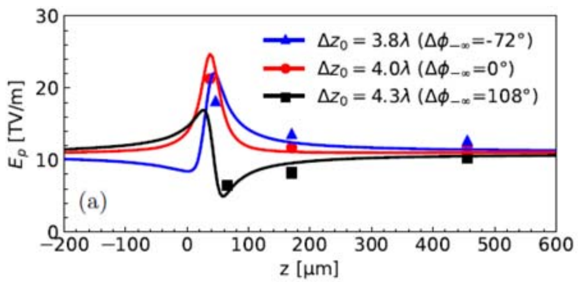


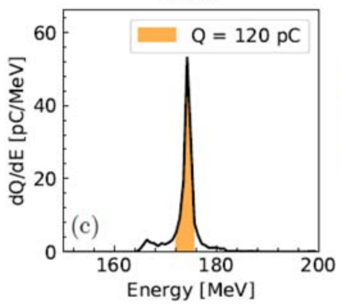
- **Published on PPCF (CAS Q2)**
- **Test experiment @ July @ SJTU**

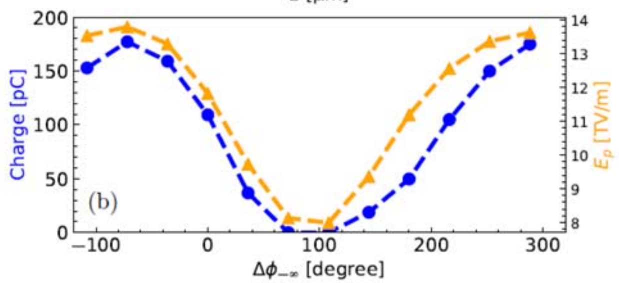
Improved injection via bubble evolving

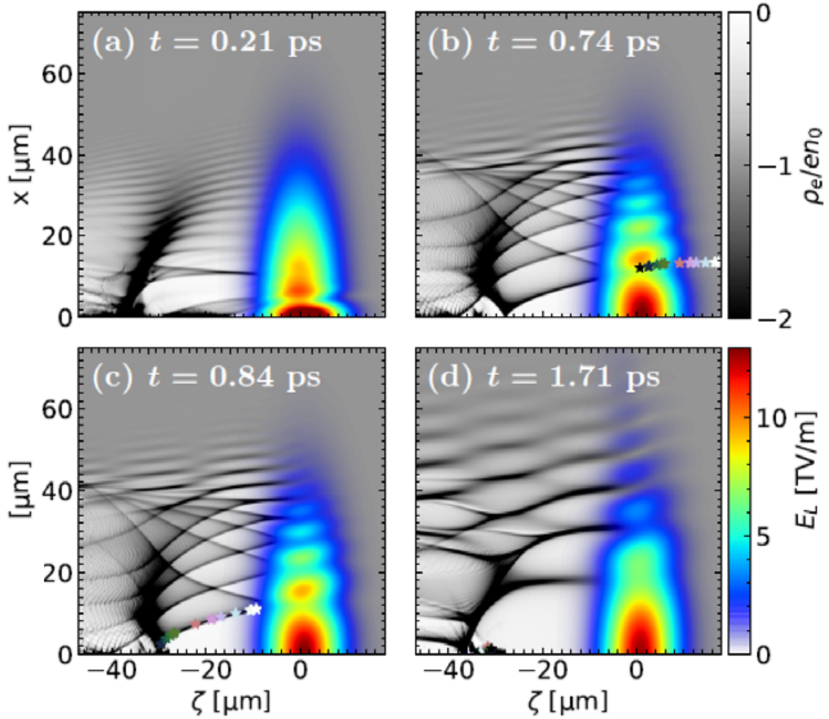












- **In simulation, with 230 TW laser, we can get ~ 750 MeV, 130 pC, 0.4% e- beam**
- **Sensitive to 2-laser time delay (sub fs)**
- **Proposed a realistic experiment @ Huairou**
- **Manuscript V1.0 is done**

Summary and prospects

- **Normal transformer ratio e- acceleration for CPI is studied**
  - **TR ~ 1.5 is much more stable and seems acceptable.**
  - **Start-to-end simulation is ongoing, together with tolerance analysis**
  - **Some other powerful damping mechanisms in a real PWFA could be used to improve the hosing instability. 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**
- **Optimal beam-loading for 2-bunch PWFA is studied**
  - **2 fitting formulas are given. It's important for designing a PWFA**
- **Some studies on controlled injection in LWFA are presented**
  - **It's crucial for a LPA injector for future light sources**

Thank you!