# High Energy CEPC Injector Based on Plasma Wakefield Accelerator

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Workshop on the Circular Electron-Positron Collider
May 25, 2018
Rome, Italy

# AARG

## A joint effort of IHEP and Tsinghua

- **Institute of High Energy Physics (IHEP)**

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- **Tsinghua University**

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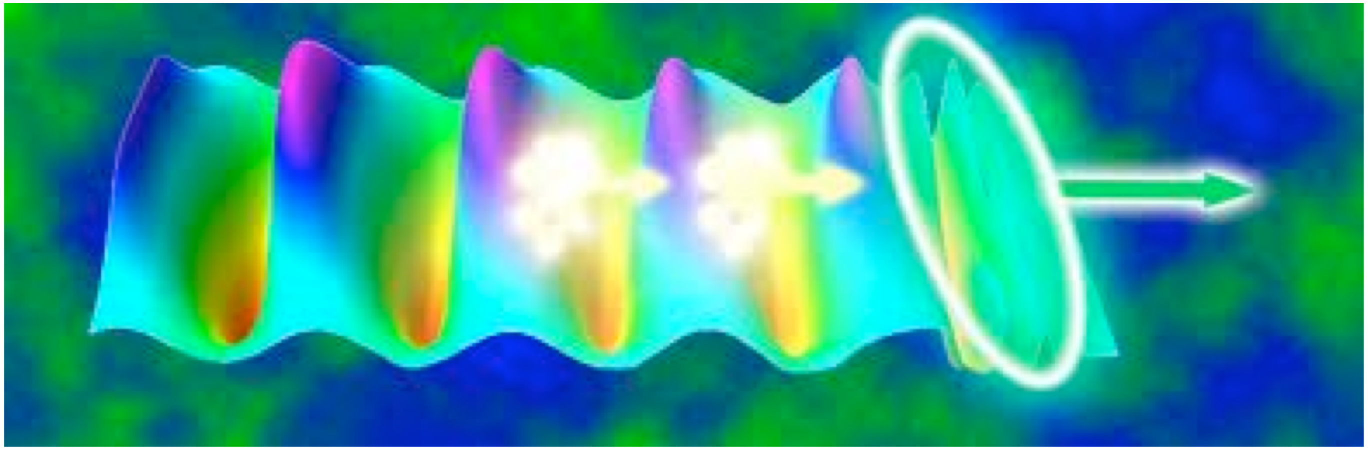
# Outline

- **Plasma based wakefield accelerator (PWFA)**
  - Key accelerator physics for PWFA
- **Plasma based injector for CEPC**
  - Boundary conditions
  - Overall concept design
  - Preliminary design parameters

# Plasma Based Wakefield Acceleration

- Trailing beam
- Laser or beam Pulse



Wake

**Huge gradient (~100GV/m) + Tiny structures (~10-100um)**

T. Tajima and J. M. Dawson PRL (1979) **LWFA**
P. Chen, J. M. Dawson et.al. PRL (1983) **PWFA**

# Important progress in past decade

# Key physics issues for a plasma accelerator

**From "Acceleration" to "Accelerator"**

- **The structure issue:**

  **Wake excitation for given drivers ……**

- **The energy spread and efficiency issue:**

  **Beam loading, pulse shaping, transformer ratio ……**

- **The stability issue:**

  **Driver evolution, matching, guiding, instabilities ……**

- **The injector issue:**

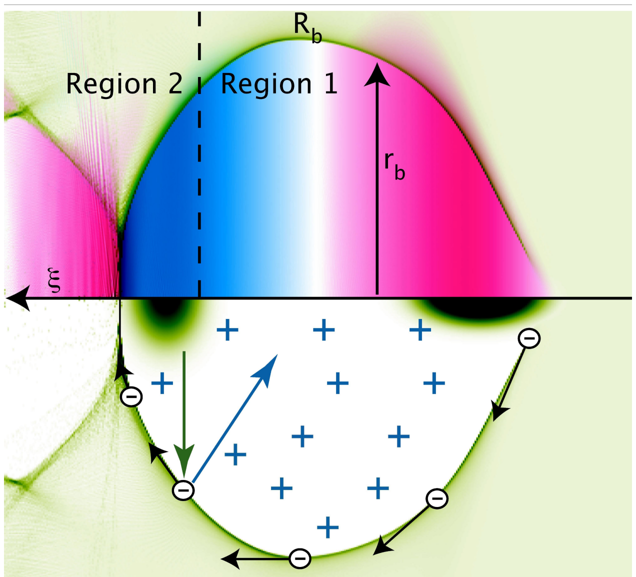
  **Self-injection, wave breaking, controlled injection ….**

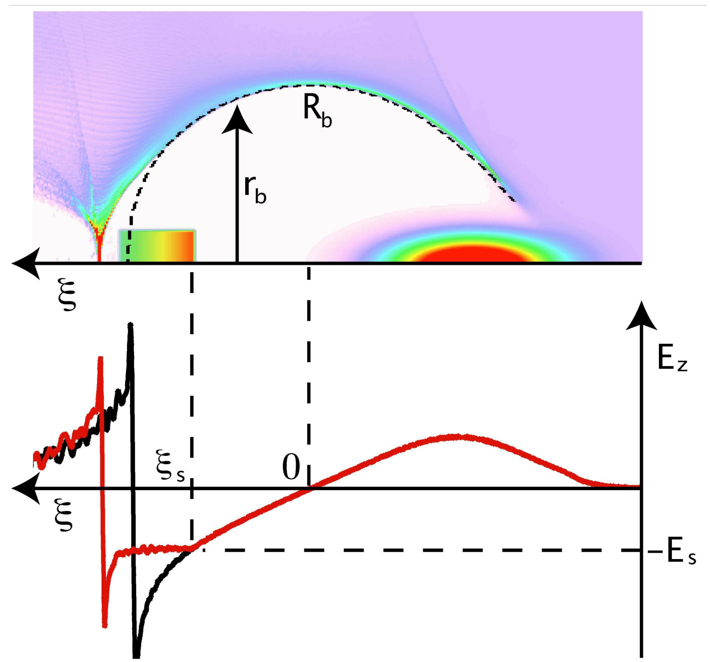
- **The overall design and staging issue:**

  **Parameter optimization for a plasma based accelerator to match requirements of beam parameters, staging, external injection ….**

# Beam loading efficiency and energy spread

**High efficiency (near 100%) + Uniform acceleration**




$$r_b \frac{d^2 r_b}{d\xi^2} + 2\left[\frac{dr_b}{d\xi}\right]^2 + 1 = \frac{4\lambda(\xi)}{r_b^2} = \frac{4\Lambda(r_b)}{r_b^2}$$

$$E_z(r,\xi) \simeq \frac{1}{2} r_b \frac{dr_b}{d\xi}$$

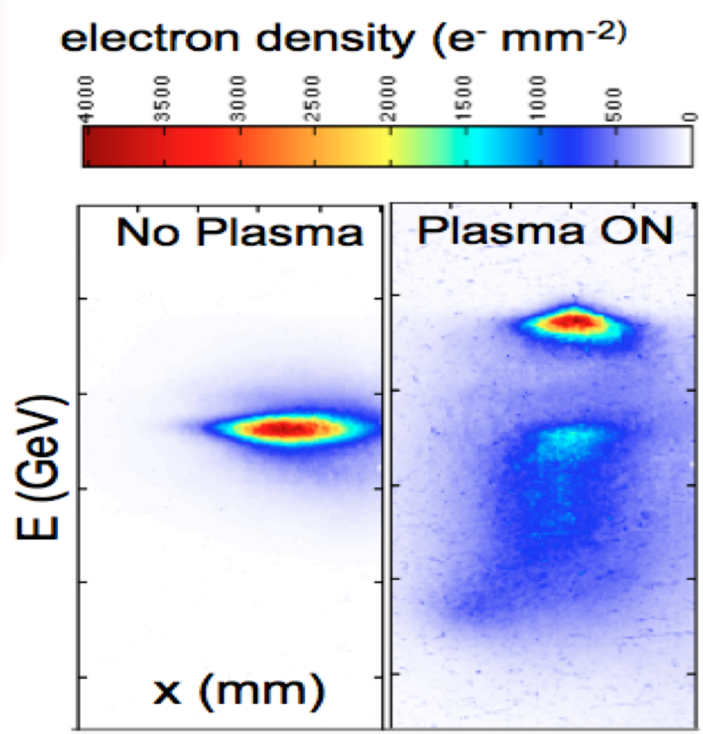
$$\Rightarrow$$

$$E_z \simeq \frac{1}{2} r_b \frac{dr_b}{d\xi} = -\frac{r_b}{2\sqrt{2}} \sqrt{\frac{16 \int^{r_b} \Lambda(\zeta)\zeta d\zeta + C}{r_b^4} - 1}$$

M. Tzoufras, W. Lu et al., PRL (2008), PoP [invited] (2009)

# Verified through Experiment

## 30-50% energy conversion efficiency

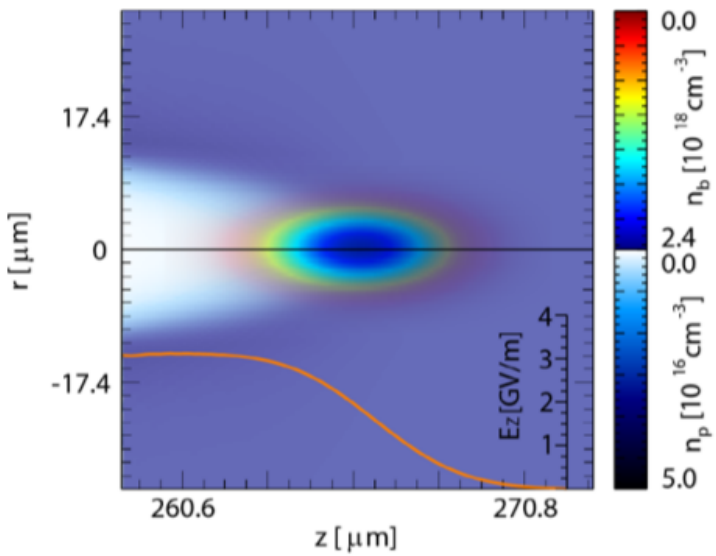


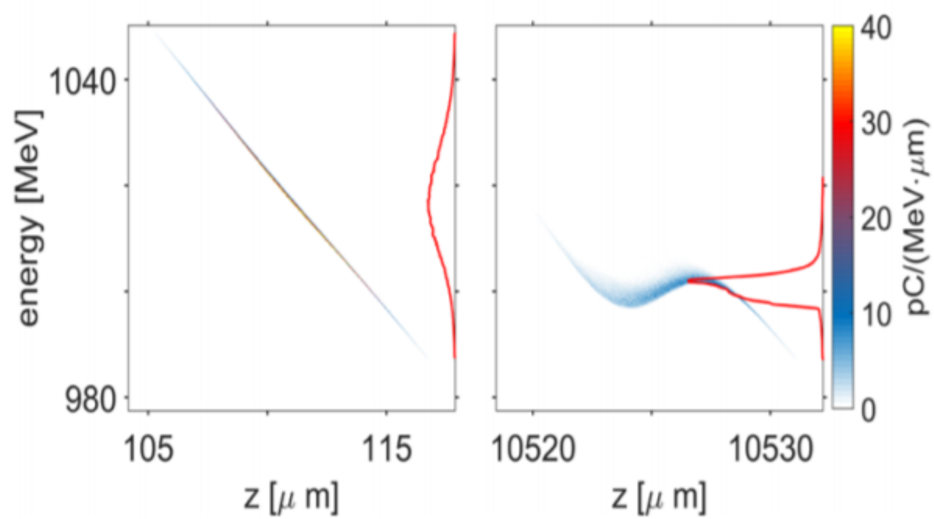


Nature **515** (2014)

# 0.1% level energy spread by plasma dechirper

- Theory and simulation show that a low density plasma dechirper can be used to reduce the energy spread down to 0.1% level
- Preliminary experiments have been done to confirm the effect of dechirping

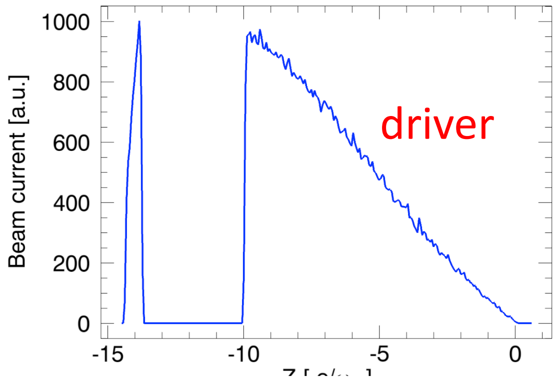


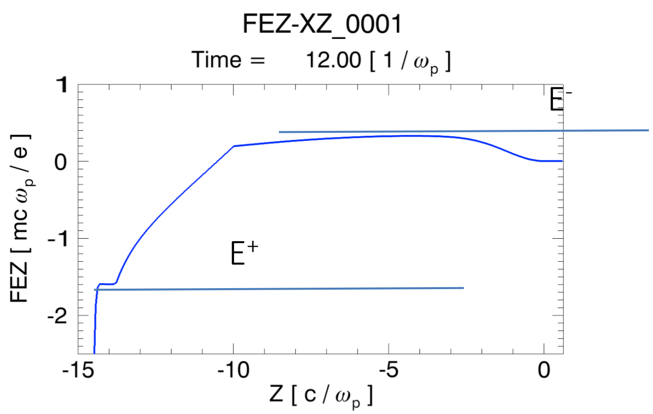



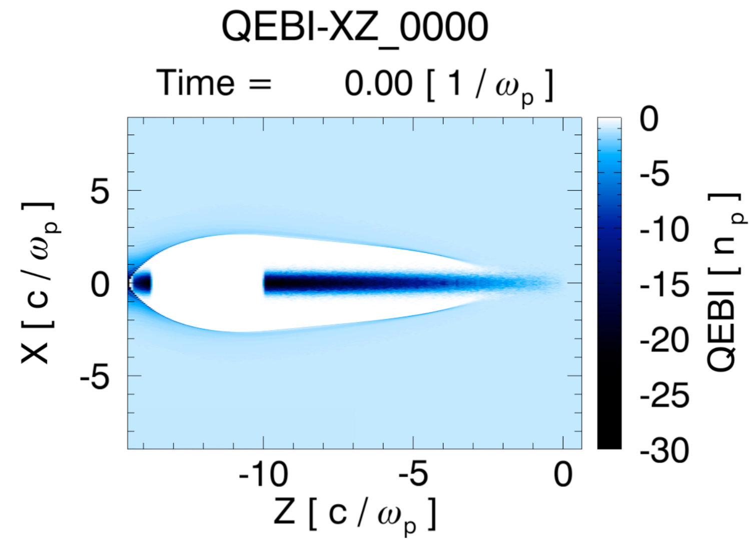

Wu, Y. *et al.* A preliminary experimental study of energy chirp reduction by a plasma dechirper. *Proc. IPAC2017* **TUOBB1,** 1258–1260 (2017)

# High Transformer Ratio PWFA

Transformer ratio: TR=$E^+/E^-$

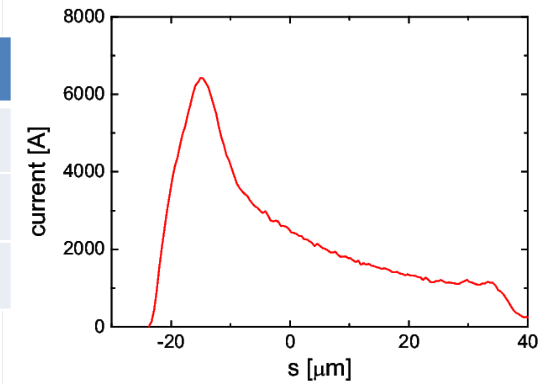



Example: shaped bunch by photo-injector of Linac

| Parameters | Value |
|---|---|
| Peak current | 6.3 kA |
| Beam length | ~200 fs |
| Initial energy | 1.5 GeV |




- **Lower Drive Beam Energy**
- **High efficiency**
- **TR=5**
- **1% energy spread**

Lu et al., PAC 2009, Huang et al., IPAC17

# Plasma Based Injector for CEPC

- The boundary condition
- Overall concept design
- Driver/trailer beam generation through Photo-injector
- HTR PWFA with good stability (single stage TR=3-4, Cascaded stage 6-12, high efficiency)
- Positron generation and acceleration in an electron beam driven PWFA using hollow plasma channel (TR=1)

# CEPC CDR Linac parameters

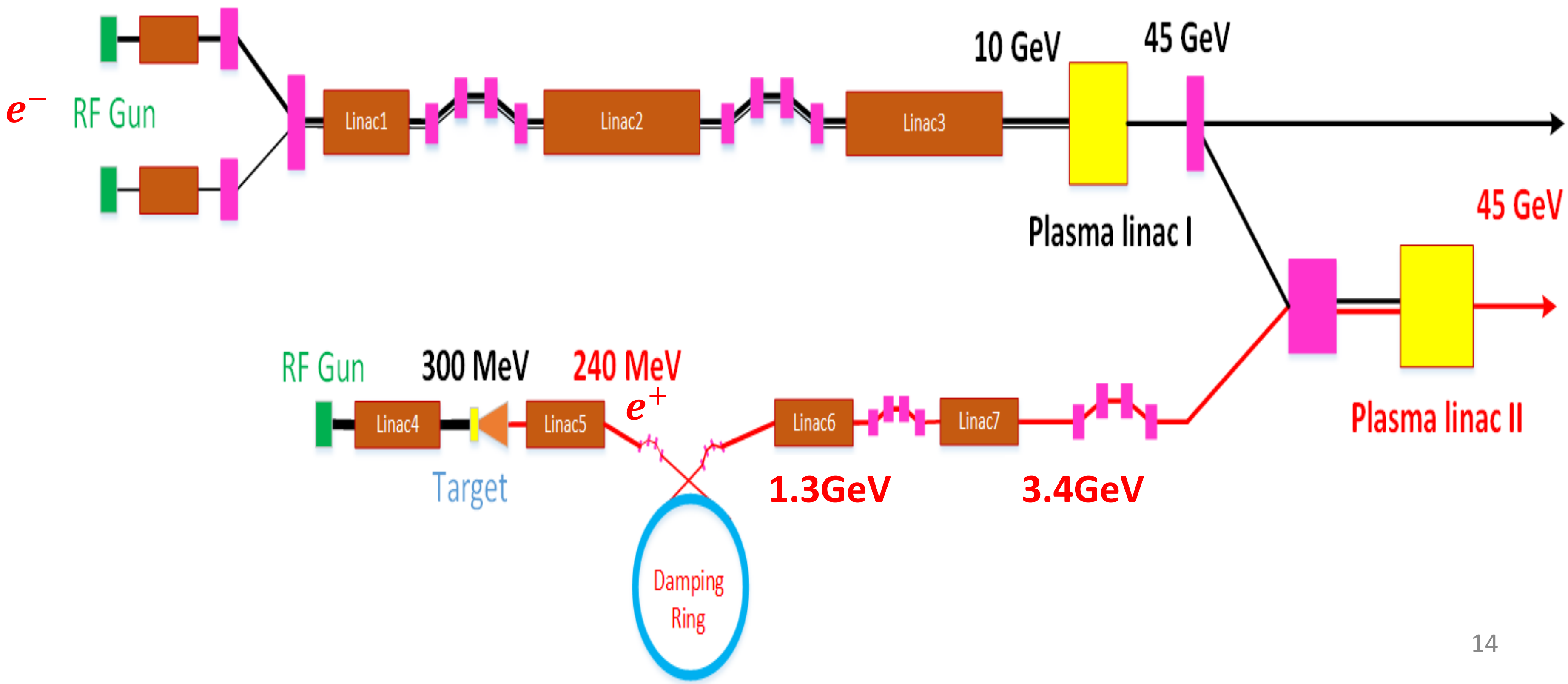
| Parameter | Symbol | Unit | CDR |
|---|---|---|---|
| $e^- / e^+$ beam energy | $E_{e-}/E_{e+}$ | GeV | 10 |
| Repetition rate | $f_{rep}$ | Hz | 50 |
| $e^- / e^+$ bunch population | $Ne-/Ne+$ | | $6.25\times10^9$ |
| | | nC | 1.0 |
| Energy spread ($e^- / e^+$) | $\sigma_E$ | | $<2\times10^{-3}$ |
| Emittance ($e^- / e^+$) | $\varepsilon_r$ | mm·mrad | <0.3 |
| $e^-$ beam energy on Target | | GeV | 4 (**2**) |
| $e^-$ bunch charge on Target | | nC | 10 |

# Boundary Conditions

- Beam average power (kW  100Hz)
- Beam charge per-bunch (nC)
- Beam energy spread (0.2%)
- Beam geometric emittance (<0.3mm mrad)
- Positron generation and acceleration

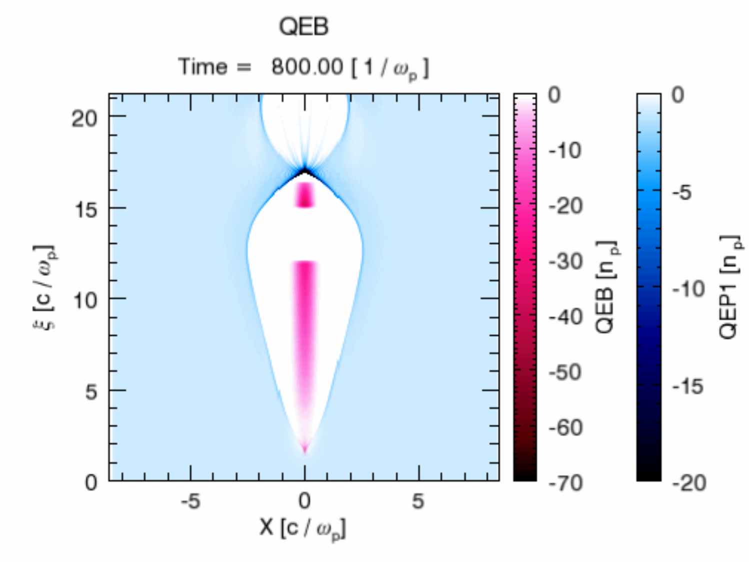
# Overall Concept Design

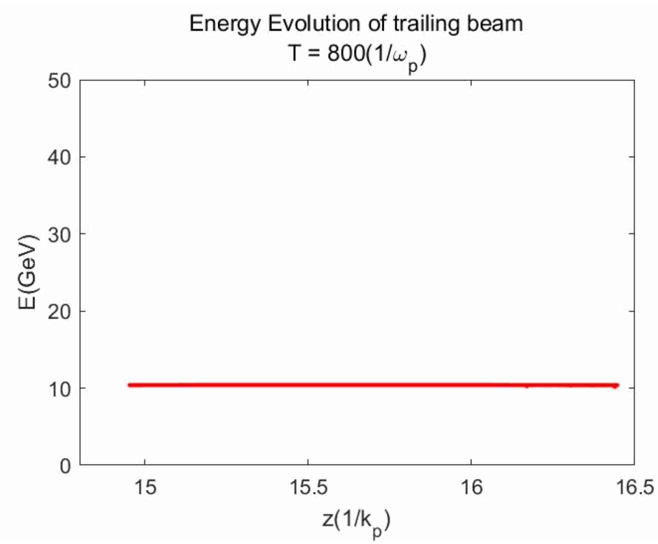
- Driver/trailer beam generation through Photo-injector
- HTR PWFA with good stability (single stage TR=3-4, Cascaded stage 6-12, high efficiency)
- Positron generation and acceleration in an electron beam driven PWFA using hollow plasma channel (TR=1)



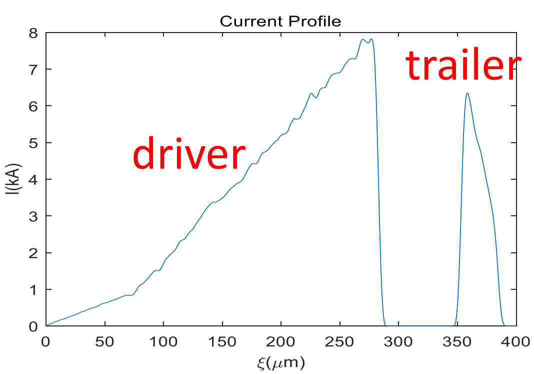
# Electron Acceleration

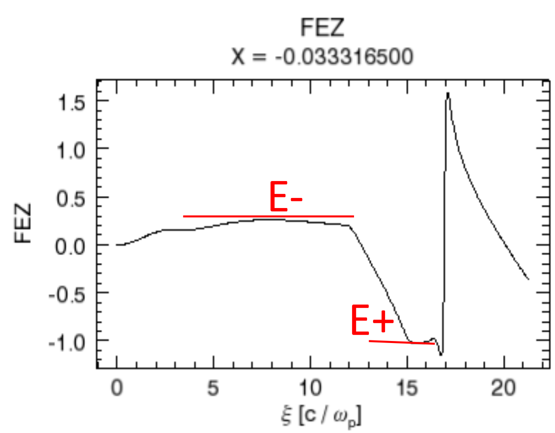
## HTR PWFA + Energy Dechirper

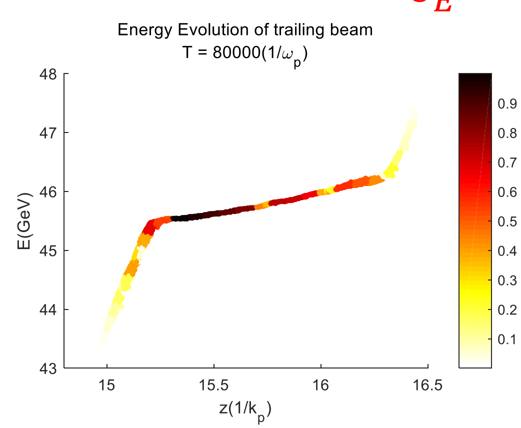



$$\delta_E = 0.62\%$$

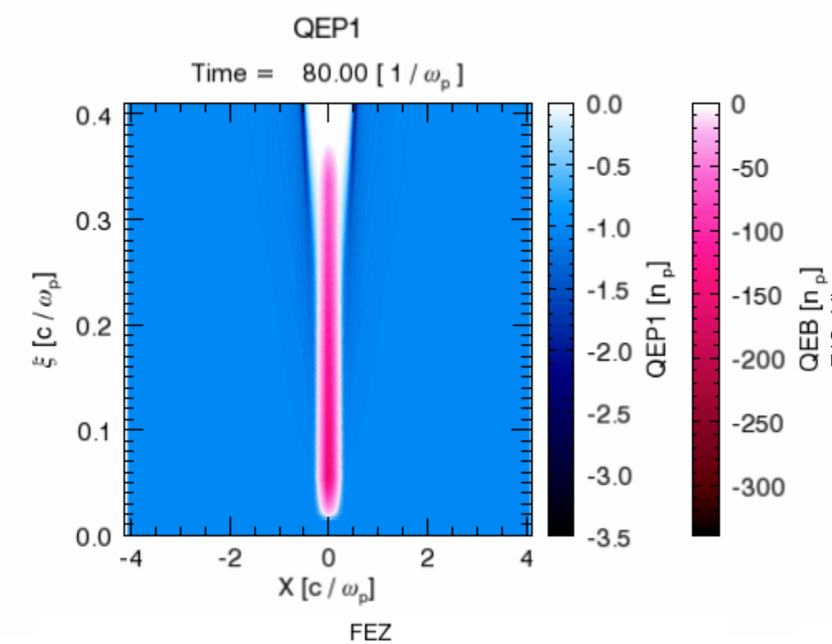


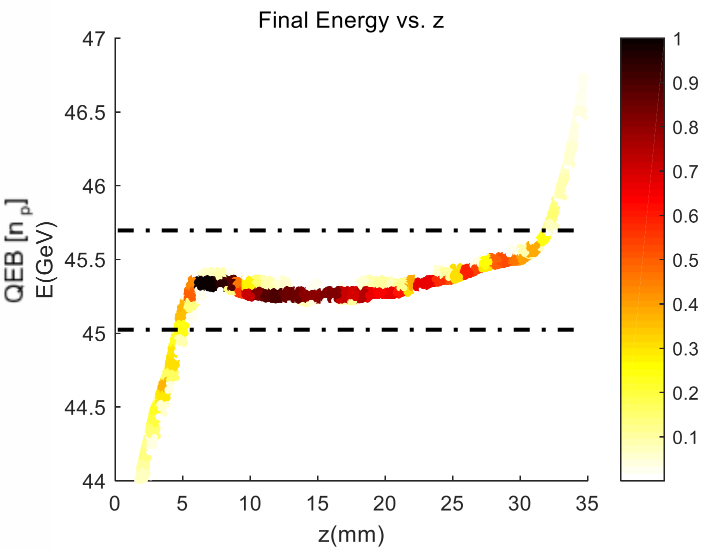



# Electron Acceleration

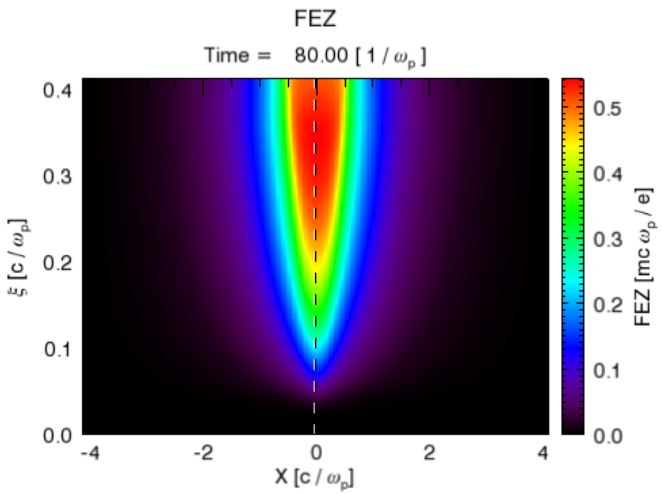
## HTR PWFA + Energy Dechirper

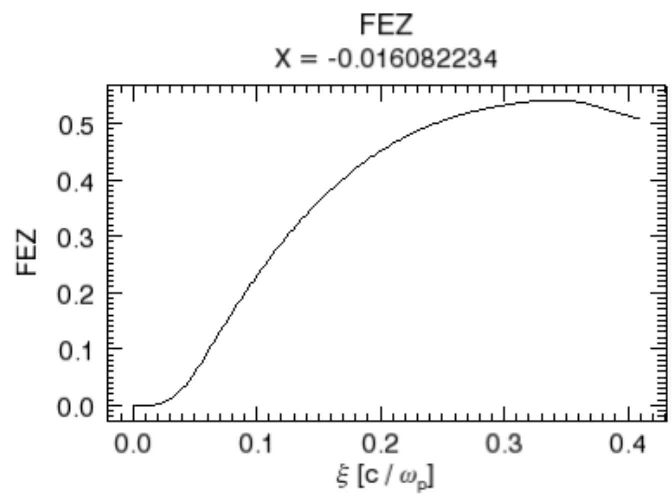



$\delta_E = 0.20\%$

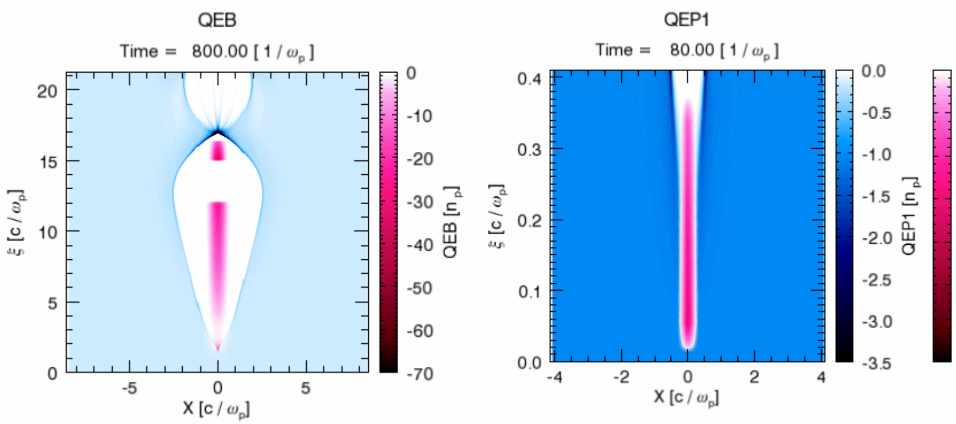
$ratio = 86.39\%$



# Electron Acceleration

## HTR PWFA + Energy Dechirper

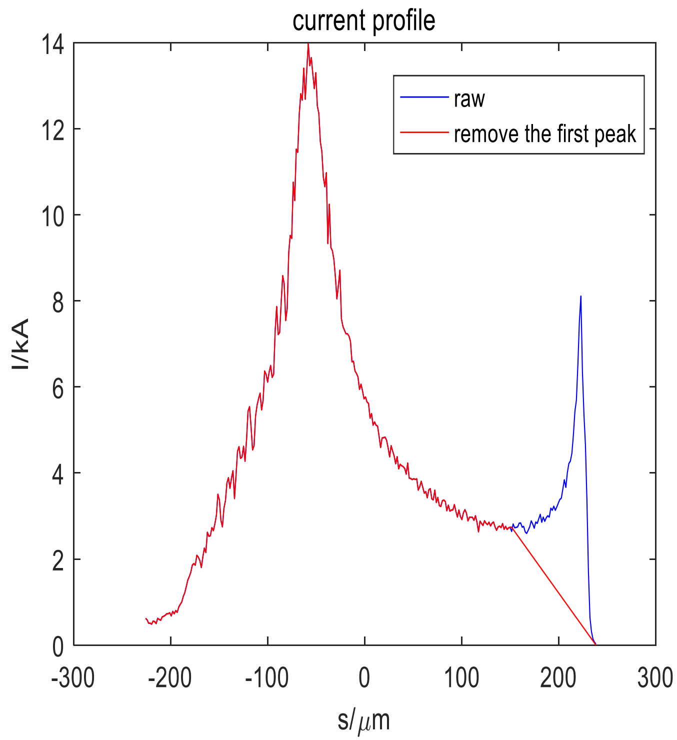


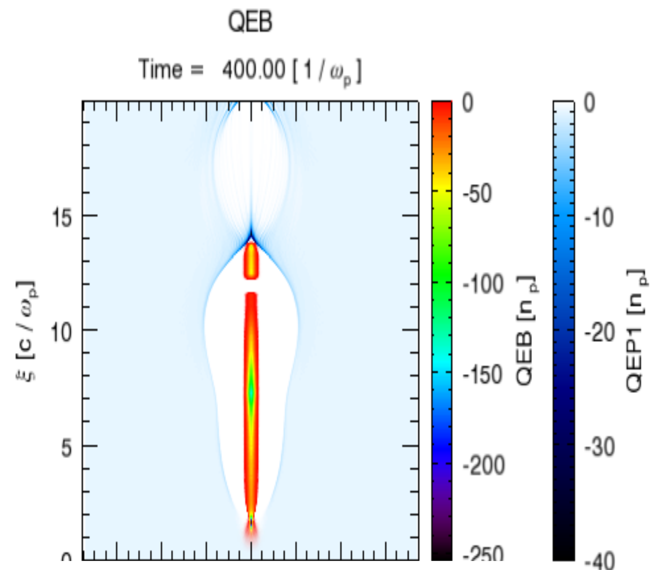

| Input parameters | |
|---|---|
| Plasma density $n_{acc}(cm^{-3})$ | $5.15\times10^{16}$ |
| Plasma density $n_{de}(cm^{-3})$ | $3\times10^{15}$ |
| Driver charge $Q_d(nC)$ | 5.18 |
| Driver energy $E_d(GeV)$ | 10 |
| Trailer charge $Q_t(nC)$ | 1.0 |
| Trailer energy $E_t(GeV)$ | 10 |
| Trailer emittance $\epsilon_t(\mathrm{nm}\ rad)$ | 5 |

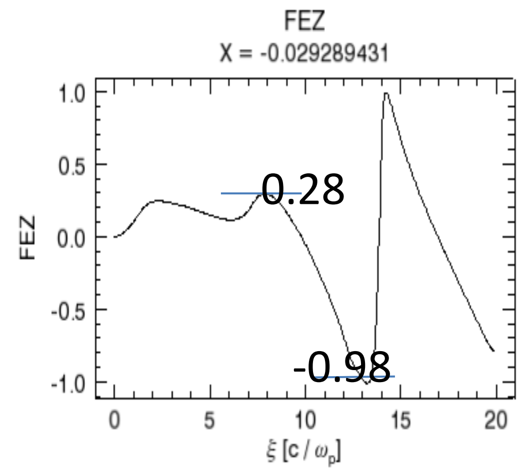
| Output parameters | HTR PWFA |
|---|---|
| Trailer energy $E_t(GeV)$ | 45.5 |
| Trailer emittance $\epsilon_t(\mathrm{nm}\ rad)$ | 1.1 |
| TR | 3.55 |
| Energy spread $\delta_E(\%)$ | 0.7 |
| Efficiency (driver -> trailer) | 68.6% |
| Plasma length (m) | 1.87 |

| Output parameters | Dechirper |
|---|---|
| trailer energy $E_t(GeV)$ | 45.3 |
| trailer emittance $\epsilon_t(\mathrm{nm}\ rad)$ | 1.89 |
| Energy spread $\delta_E(\%)$ | 0.2 |
| Overall Efficiency | 59.4% |
| Plasma length (m) | 0.23 |

# 7nC Shaped bunch by S-band photo-injector and LINAC



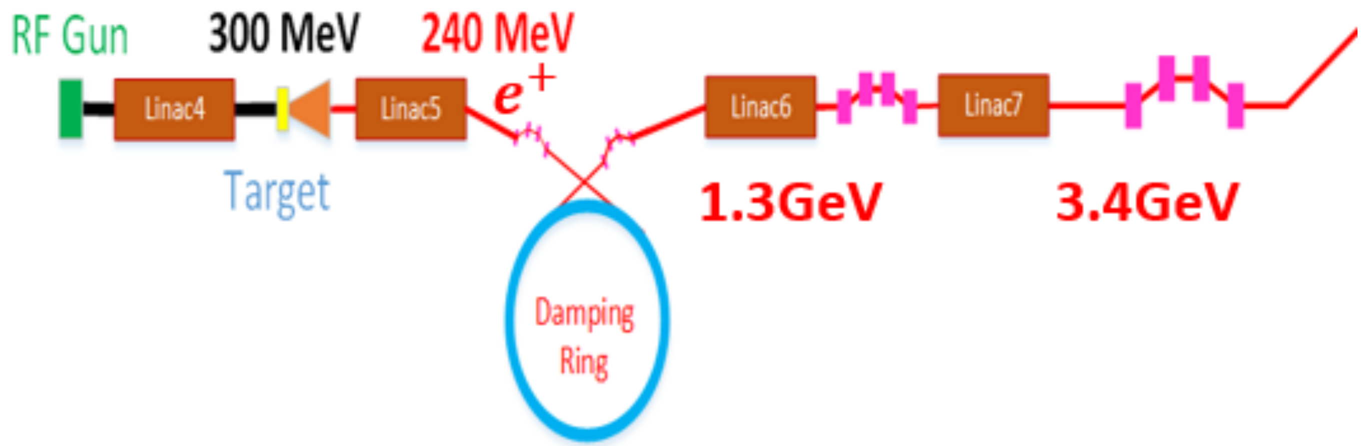




Simulation data by Zhen Wang of SINAP

$\mathrm{TR} = 3.5$

# Positron generation



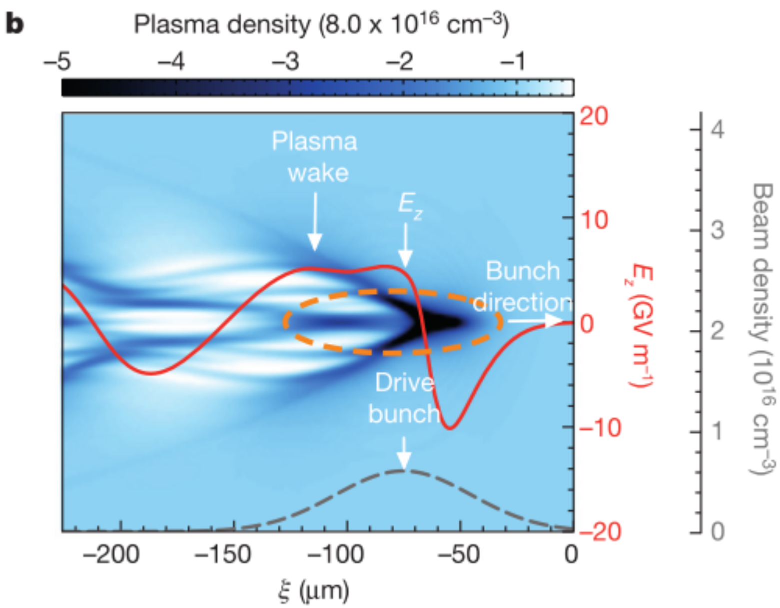

Compression ratio：
BCI：8.2
BCII：4.4
BCIII：3.3

| Output parameters | |
|---|---|
| Final energy $E(GeV)$ | 3.4 |
| Energy spread $\delta_E(\%)$ | 2.0 |
| Beam length $\sigma_z(\mu m)$ | 15 |

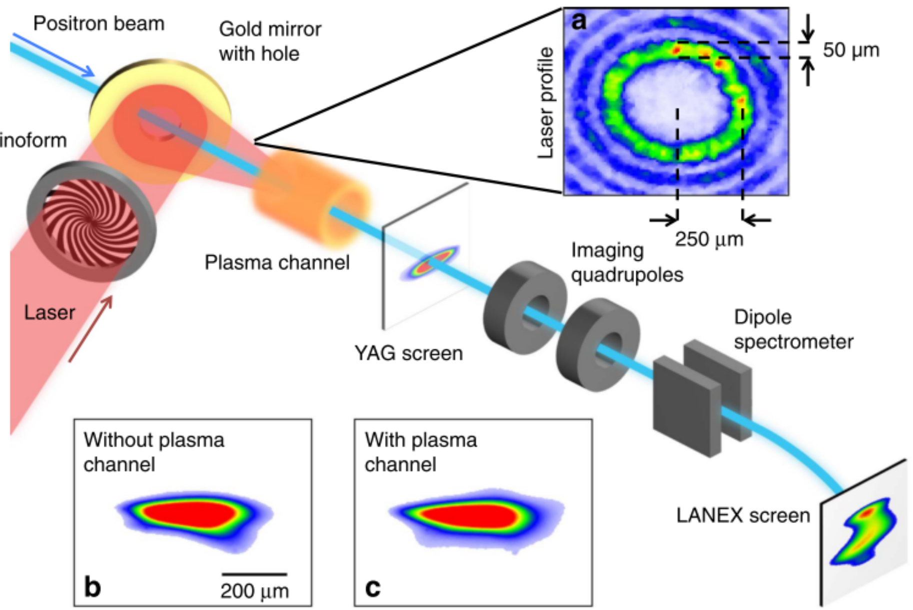
By Dou Wang

# Positron Acceleration

**Positron self-loading**




**Hollow plasma channel**

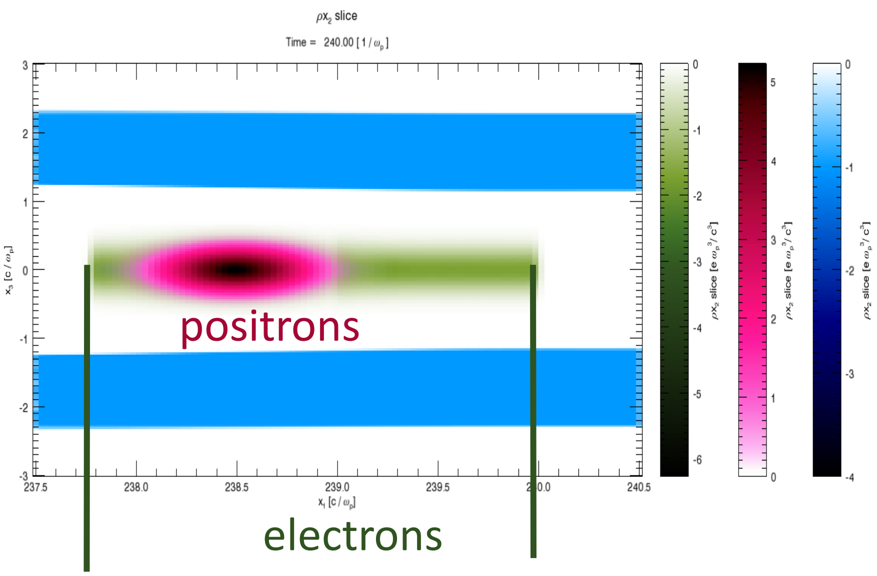


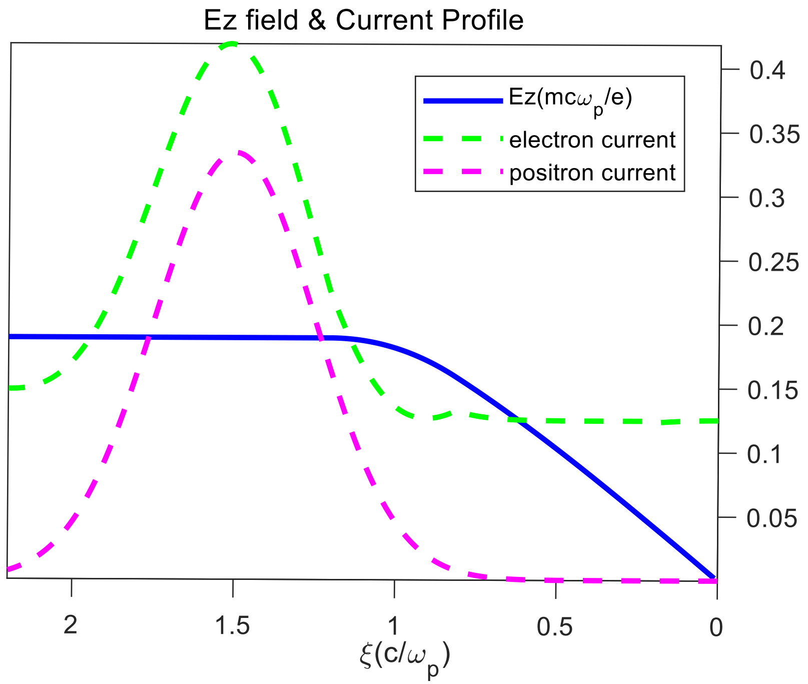

Corde, S, et al. *Nature* (2015).

Gessner, Spencer, et al. *Nature Communications* (2016).

# Positron Acceleration

**Uniform acceleration + High efficiency + TR=1**



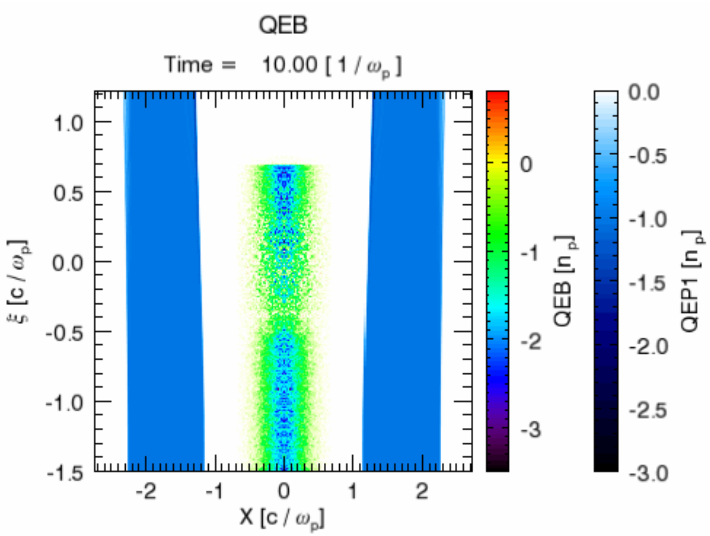



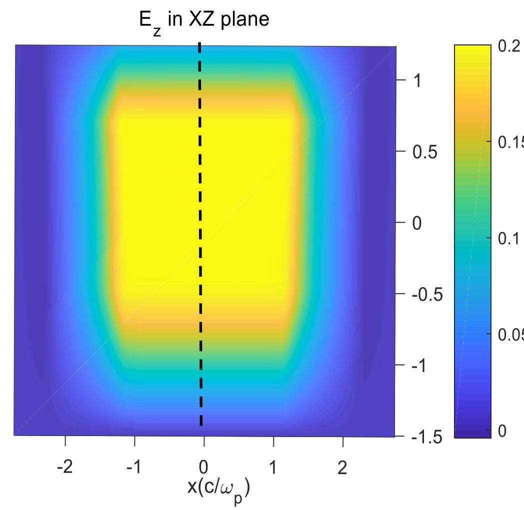

By Shiyu Zhou

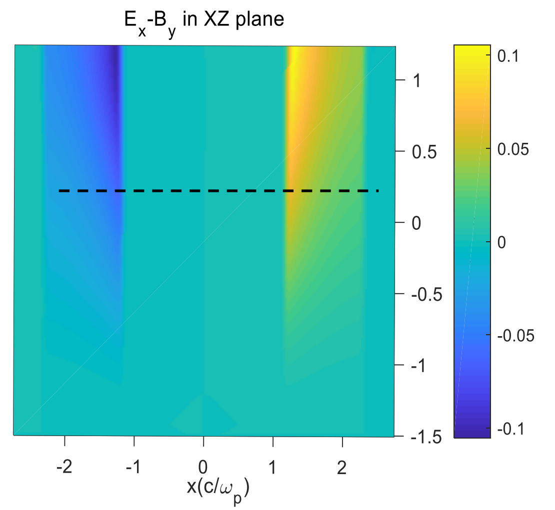
# Positron Acceleration

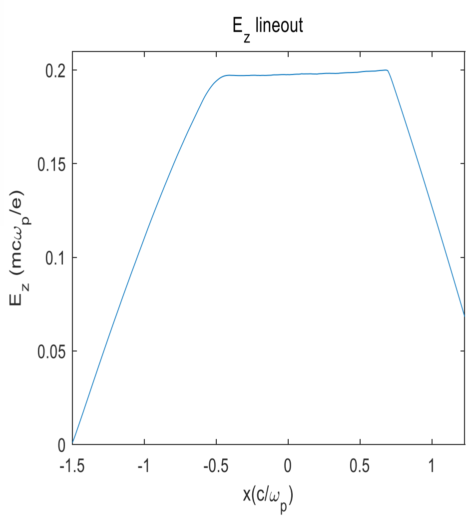
## Uniform acceleration + High efficiency + TR=1

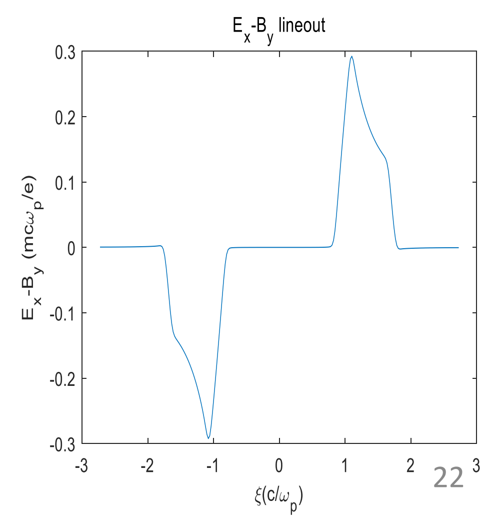
### Fields Structure



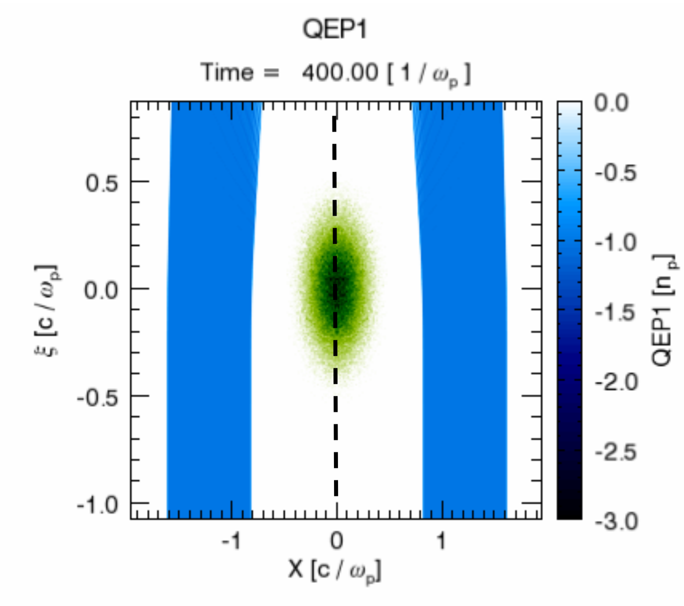



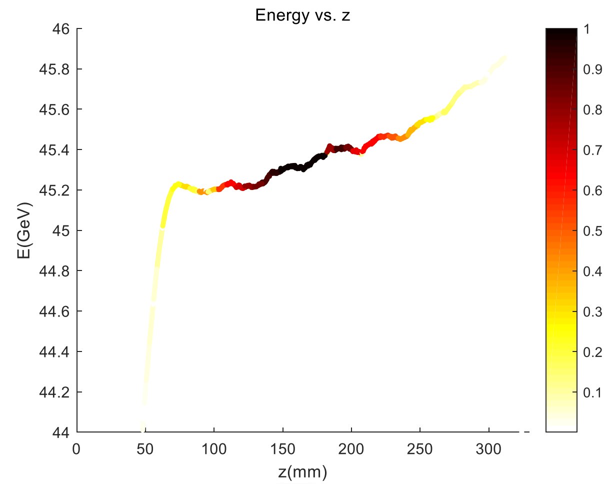



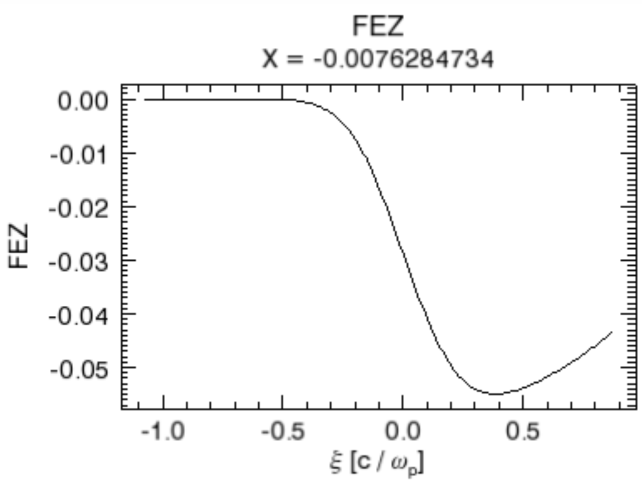



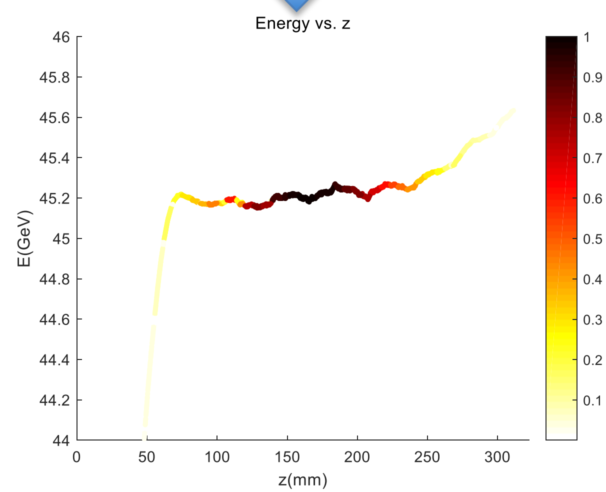
# Positron Acceleration

## Energy Dechirper



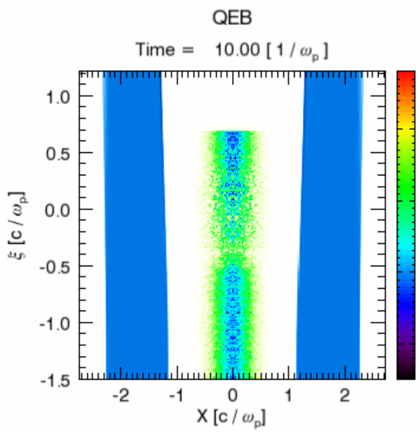



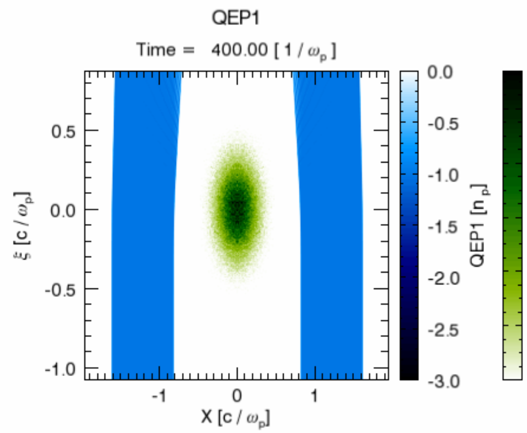



# Positron Acceleration

## Beam Combine+ Energy Dechirper



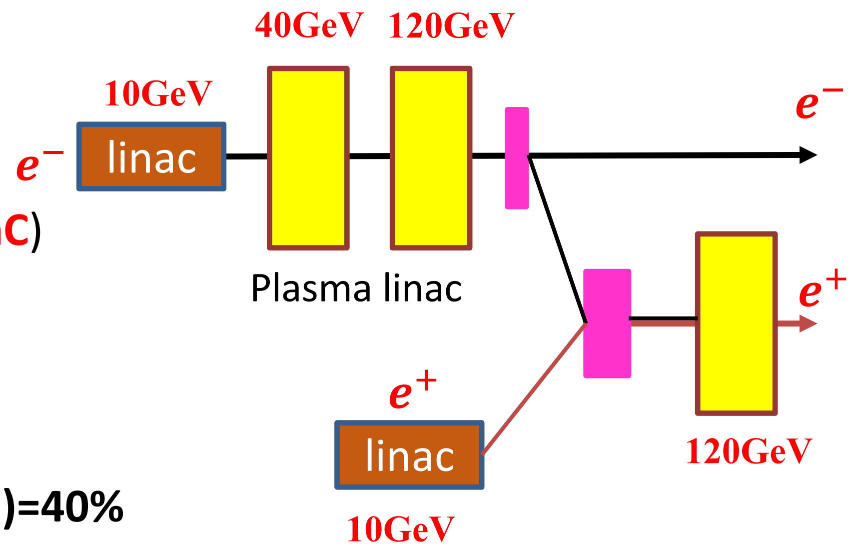

| Input parameters | |
|---|---|
| Plasma density $n_{acc}(cm^{-3})$ | $1.77\times10^{16}$ |
| Plasma density $n_{de}(cm^{-3})$ | $0.91\times10^{16}$ |
| Driver charge $Q_d(nC)$ | 2.1 |
| Driver energy $E_d(GeV)$ | 45 |
| trailer charge $Q_t(nC)$ | 1.0 |
| trailer energy $E_t(GeV)$ | 3.4 |
| trailer emittance$\epsilon_t(\mathrm{nm}\ rad)$ | 13 |

| Output parameters | Acceleration |
|---|---|
| trailer energy $E_t(GeV)$ | 45.3 |
| trailer emittance $\epsilon_t(\mathrm{nm}\ rad)$ | 1.0 |
| TR | 1 |
| Energy spread $\delta_E(\%)$ | 0.29 |
| Efficiency (driver -> trailer) | 46.82% |
| Plasma length (m) | ~22 |

| Output parameters | Dechirper |
|---|---|
| trailer energy $E_t(GeV)$ | 45.2 |
| trailer emittance $\epsilon_t(\mathrm{nm}\ rad)$ | 1.0 |
| Energy spread $\delta_E(\%)$ | 0.14 |
| Overall Efficiency | 45.4% |
| Plasma length (m) | 1.47 |

# Cascaded HTR PWFA

- **The 1st stage**
  - Two shaped bunches (**2.5ps 25nC, 500fs 5nC**)
  - TR=2 or 3
  - Efficiency (**60%**)
- **The 2nd stage**
  - Controlled injection for e (**100fs 1nC or 2nC**)
  - TR=2 or 3
  - Single stage efficiency (**60%**)
  - Overall **TR=(1+TR1)*TR2**
- Overall efficiency **Q3(1+TR1)*TR2/(Q1+Q2)=40%**
- **The positron stage**
  - Combining e+ with e- (**50fs 1nC** )
  - TR=1 Single stage efficiency (**~50%**)
  - Overall efficiency for positron **20%**



# Summary

- e-/e+ acceleration to 45 GeV in HTR PWFA with single stage TR=3.5 is possible (10GeV electron beam driver)

- e-/e+ acceleration to 100 GeV level in Cascaded HTR PWFA with TR=10 is possible (10GeV electron beam driver with higher charge)

- Energy spread of 0.2% could be achieved by post processing using a plasma dechirper

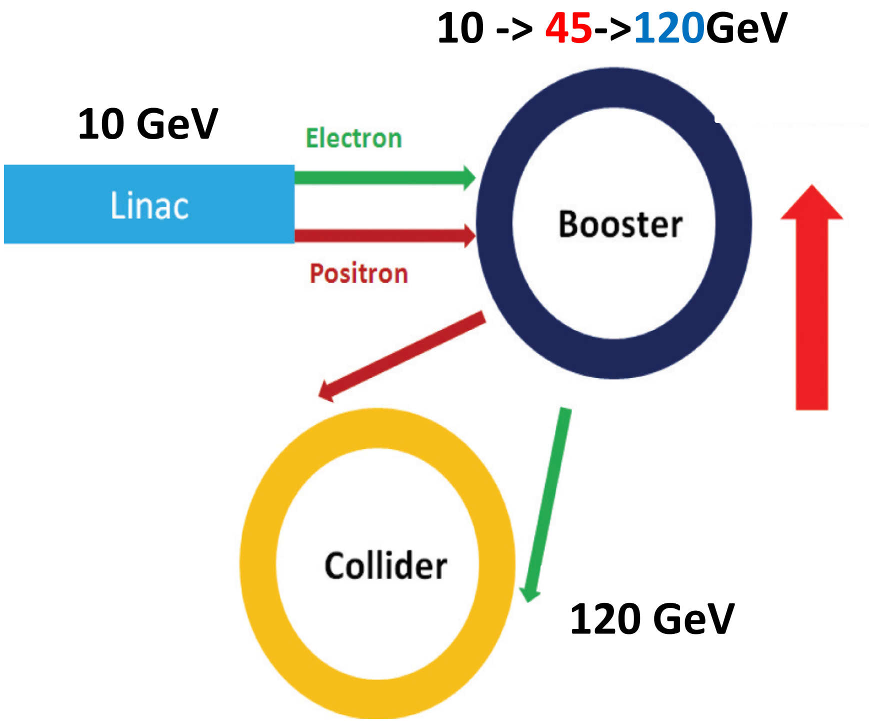
- Preliminary experimental tests could be performed in near future at FACETII of SLAC

# Thank you for your attention!

# Summary

- **Single stage HTR PWFA**
  - 45GeV
  - TR=3~3.5
  - Efficiency (**60%/30%**)

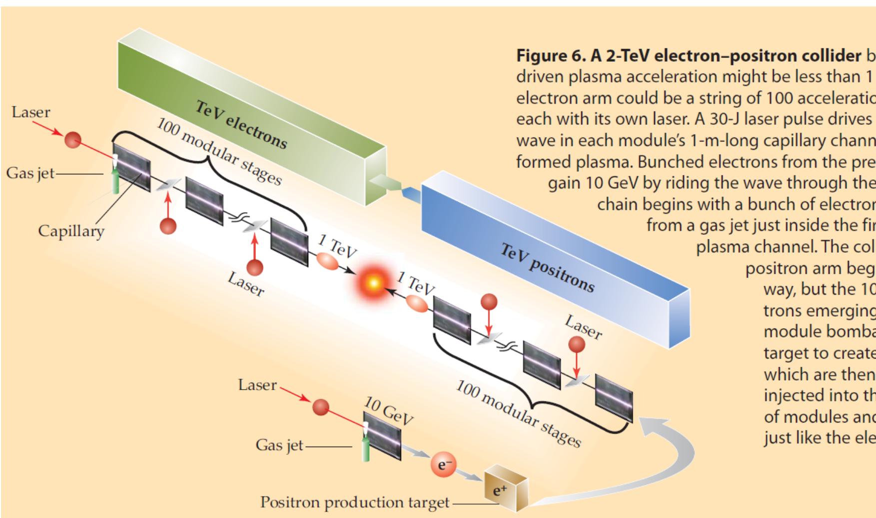
- **Cascaded HTR PWFA**
  - 120GeV
  - TR=3
  - Efficiency (**40%/20%**)

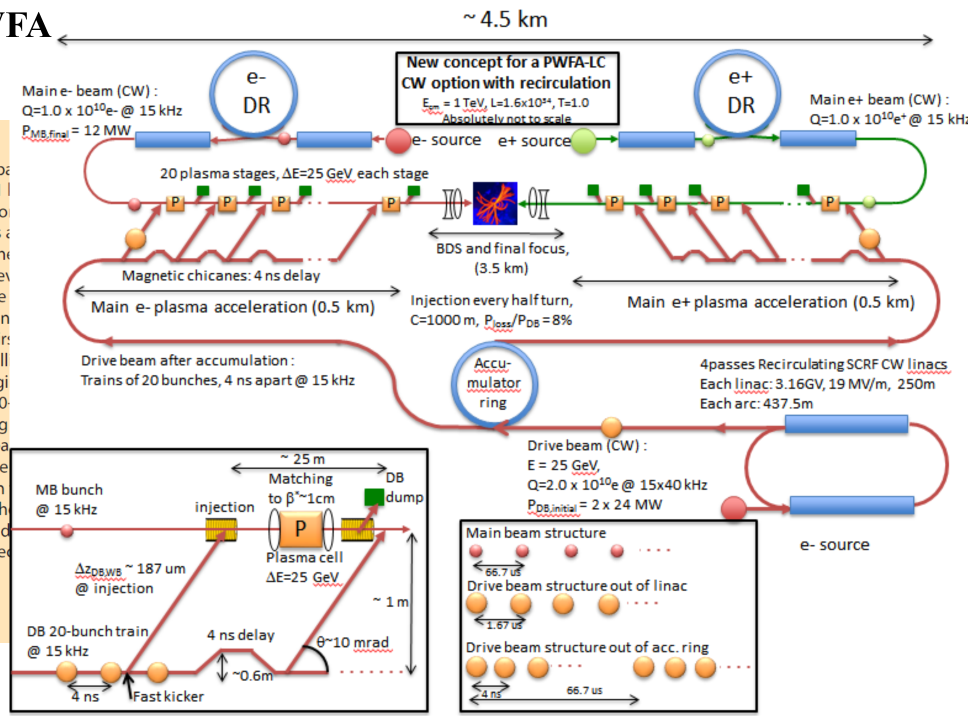


# Plasma based colliders

**Layout of 1 TeV PWFA Linear Collider**

**Layout of 2 TeV electron-positron collider based on LWFA**



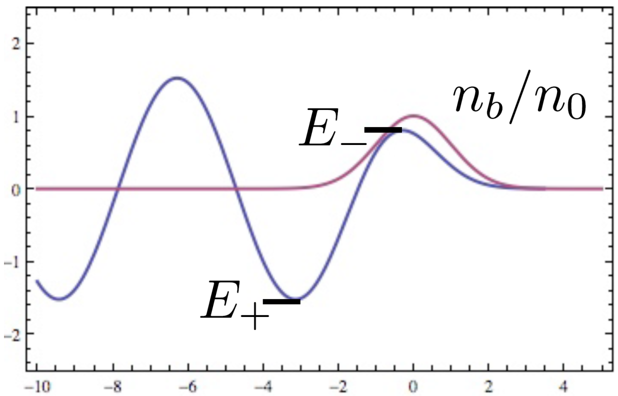

Leemans & Esarey, Physics Today, March 2009

Mark Hogan, SLAC-PUB-15426, in 2013

# Transformer Ratio: limits energy gain in PWFA

**Transformer Ratio:** $R = E_+/E_- \leq 2$

- ✓ Limits energy gain in PWFA
- ✓ Under general considerations (symmetric bunches)




*P. Chen et al., Phys. Rev. Lett., 1985*

Drive beam energy depleted after distance:

$$L_d \sim \gamma_b m_e c^2 / eE_-$$

Energy gain of witness bunch: $\boxed{\Delta\gamma m_e c^2 \sim eE_+ L_d = R\left(\gamma_b m_e c^2\right)}$

**Higher transformer ratios achieved using shaped (asymmetric) bunches:**

Triangular beam: $R = \pi(L_b/\lambda_p)$ *R. Ruth et al., PA (1985)*

Bunch train: $R \leq 2\sqrt{M_b}$

Improved transformer ratio in nonlinear blowout regime using ramped bunch $R \sim \frac{L_b}{R_b}\left(\frac{n_0}{n_b}\right)^{1/2}$

*W. Lu et al., PAC, 2009*