High Energy CEPC Injector Based on Plasma Wakefield Accelerator

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AARG

A joint effort of IHEP and Tsinghua

- **IHEP**

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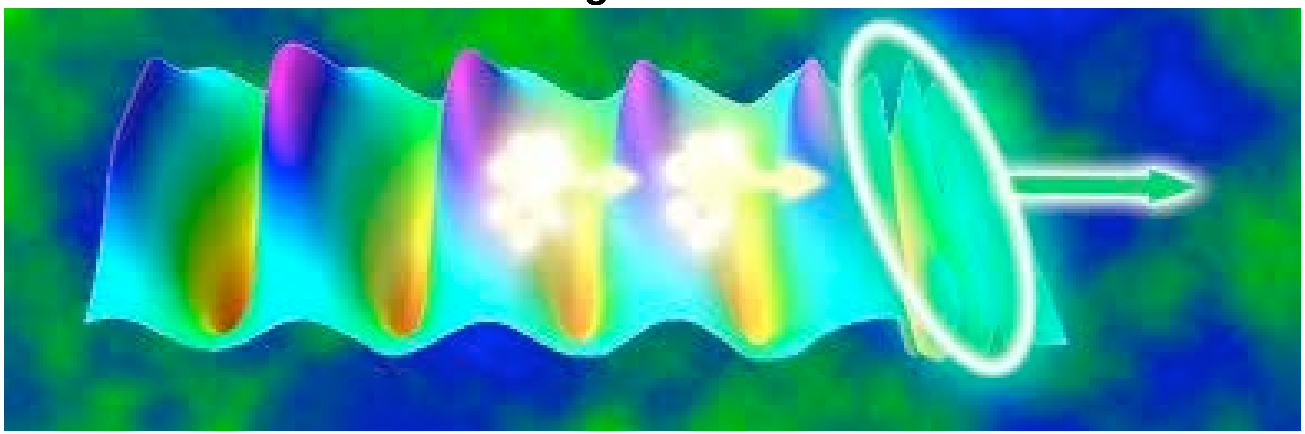
Outline

- **Plasma based wakefield accelerator (PBA)**
  - ➢ Key accelerator physics for PBA

- **Plasma based injector for CEPC**
  - ➢ Boundary conditions
  - ➢ Overall concept design
  - ➢ Preliminary design parameters

Plasma Based Wakefield Acceleration

- Laser or beam Pulse
- Trailing beam



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

- □ **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:**

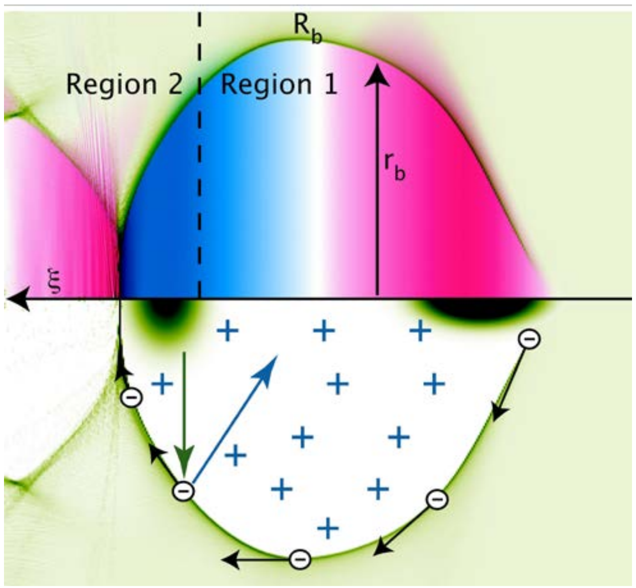
Self-injection, wave breaking, controlled injection ….

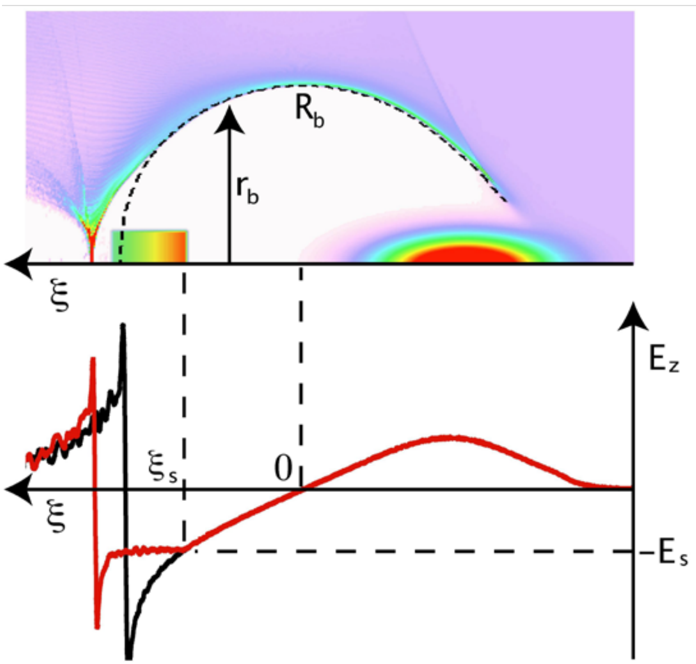
- □ **The overall design and staging issue:**

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

Beam loading efficiency and energy spread

High efficiency (near 100%) + Uniform acceleration





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

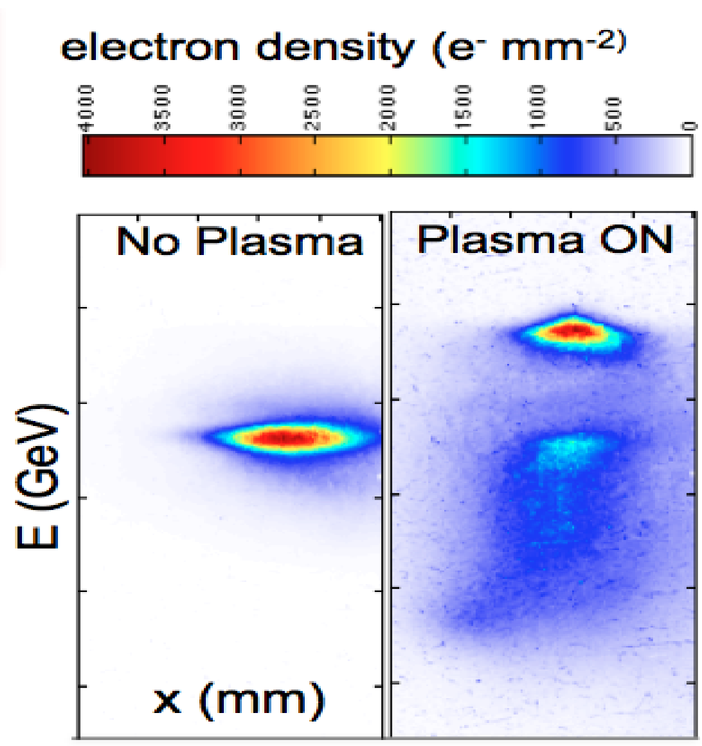
$$E_z(r,\xi) \simeq \frac{1}{2} r_b \frac{dr_b}{d\xi}$$

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

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

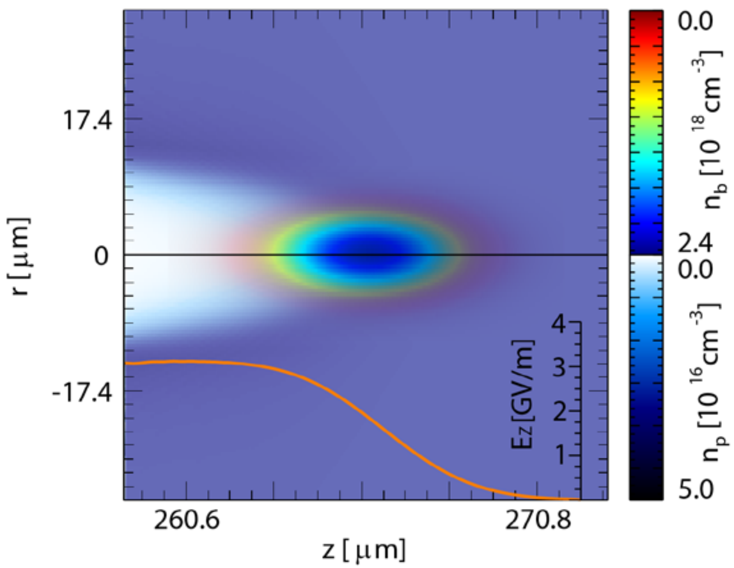
Verified through Experiment

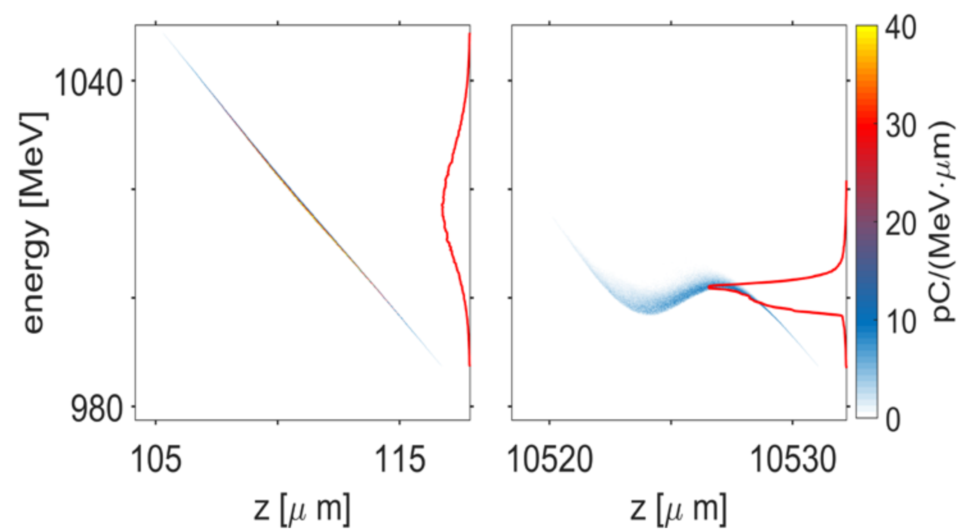
30-50% energy conversion efficiency



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

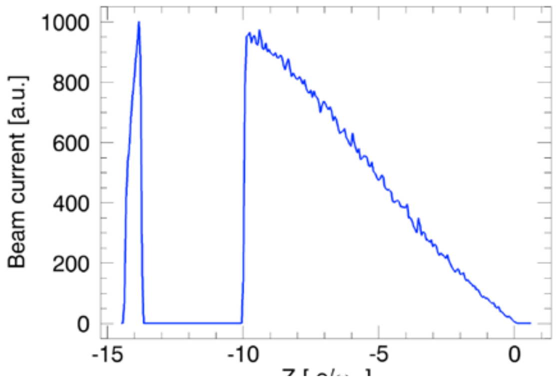


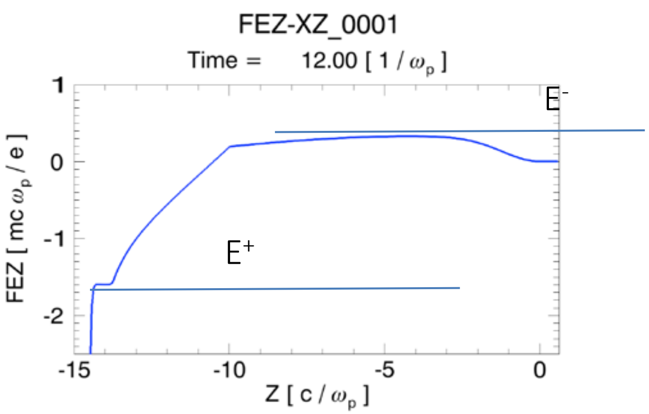


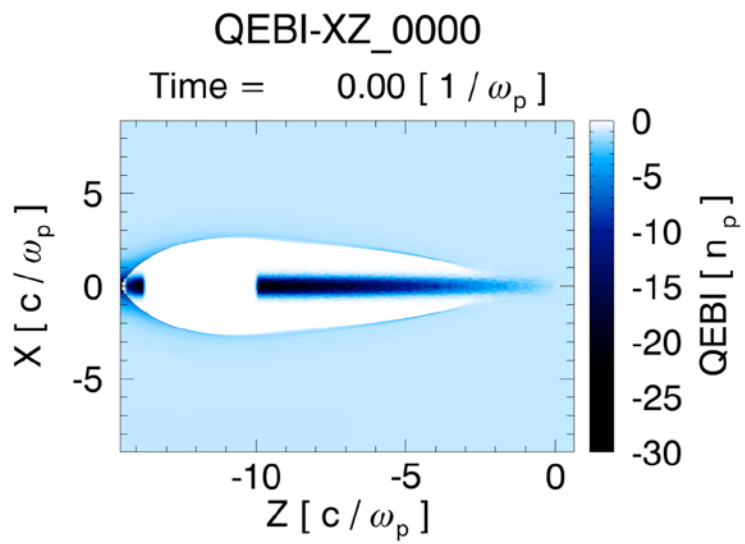
Wu, Y. *et al.* A preliminary experimental study of energy chirp reduction by a plasma dechirper. *Proc. IPAC2017* **TUOBB1,** 1258–1260 (2017)

High Transformer Ratio PWFA

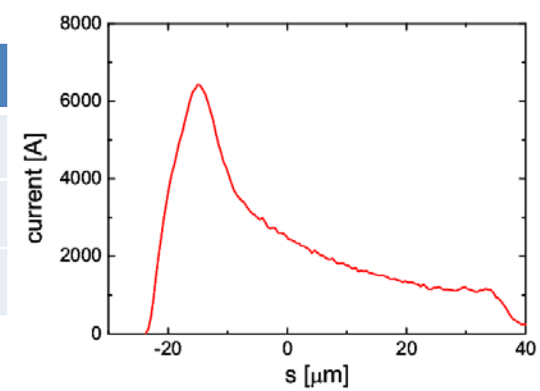
Transformer ratio: R = E^{+}/E^{-}







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 Pre-CDR/CDR Linac Requirement

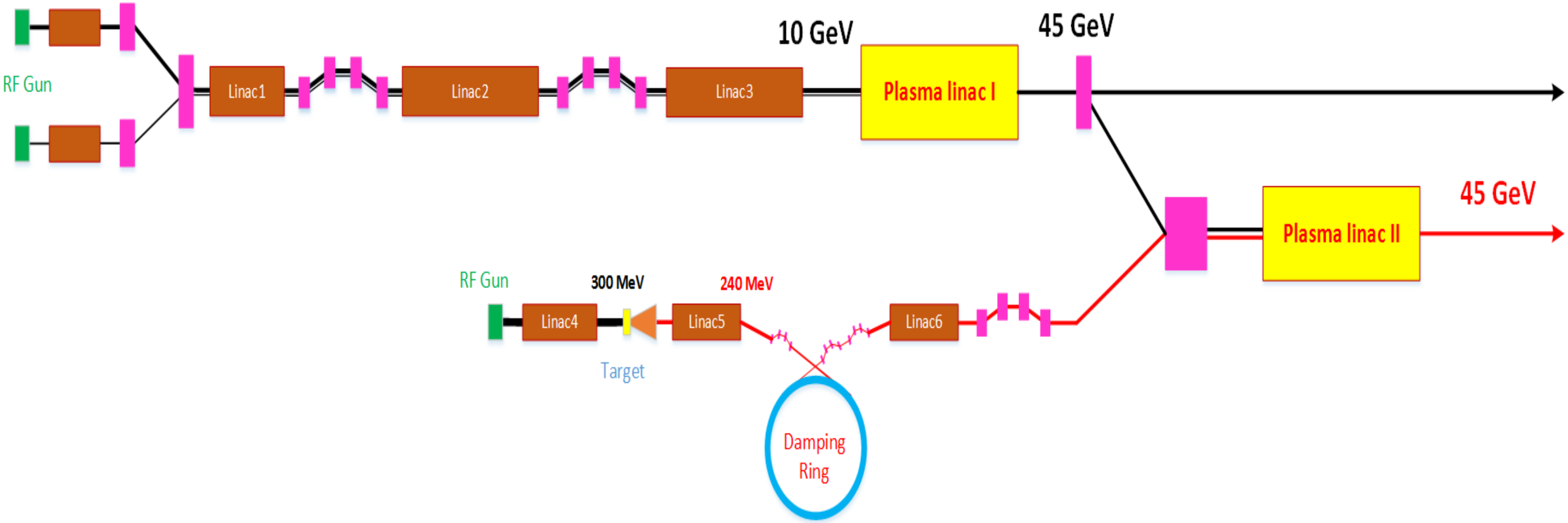
Parameter	Symbol	Unit	Pre-CDR	CDR
e^-/e^+ beam energy	E_{e-}/E_{e+}	GeV	6	10
Repetition rate	f_{rep}	Hz	50	50
e^-/e^+ bunch population	$Ne-/Ne+$		2×10^{10}	6.25×10^{9}
		nC	3.2	1.0
Energy spread (e^-/e^+)	σ_E		$<1\times10^{-3}$	$<2\times10^{-3}$
Emittance (e^-/e^+)	ε_r	mm·mrad	<0.3	<0.3
e^- beam energy on Target		GeV	4	4 (**2**)
e^- bunch charge on Target		nC	10	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)

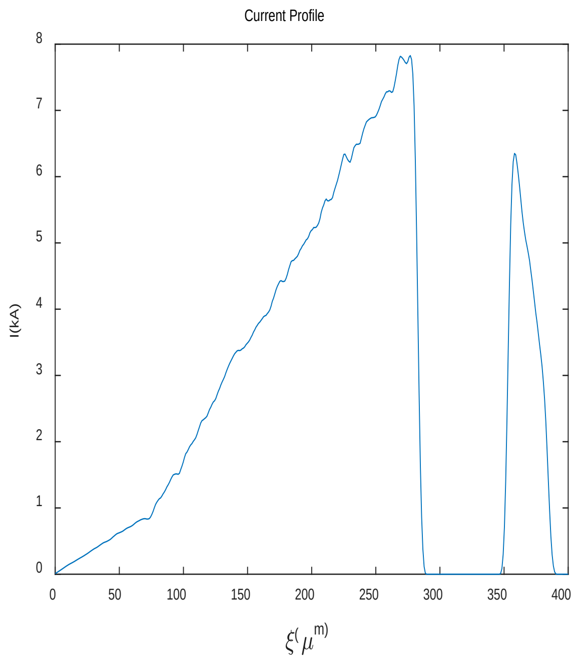


By Cai Meng et al.

HTR PWFA parameter design (TR=3.55)

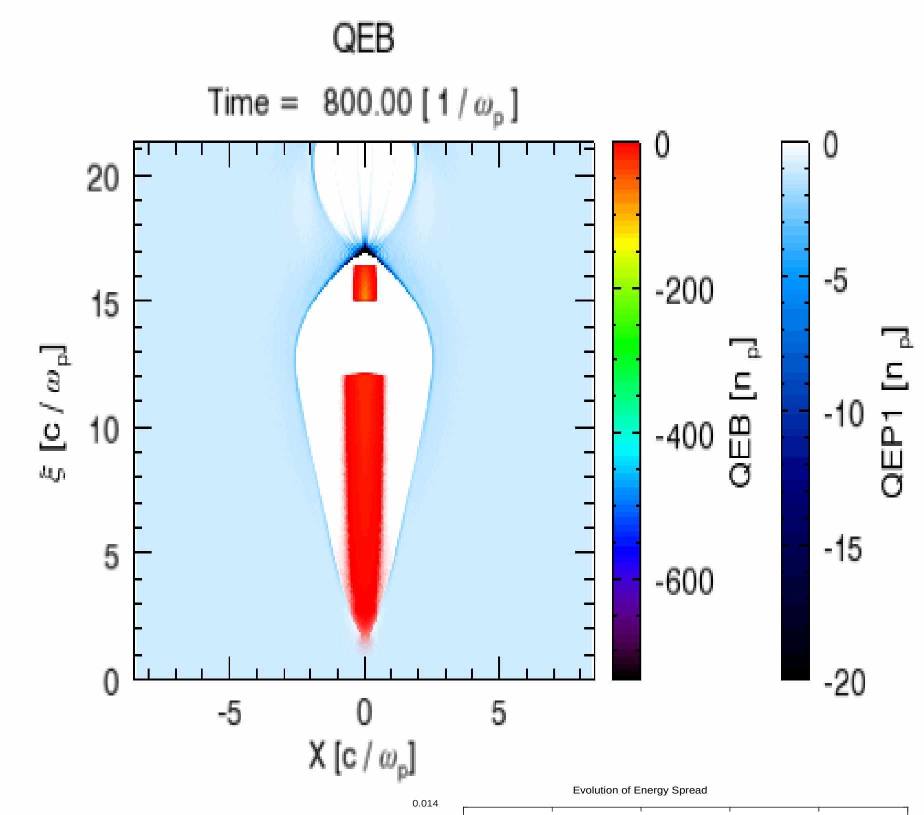
Input parameters

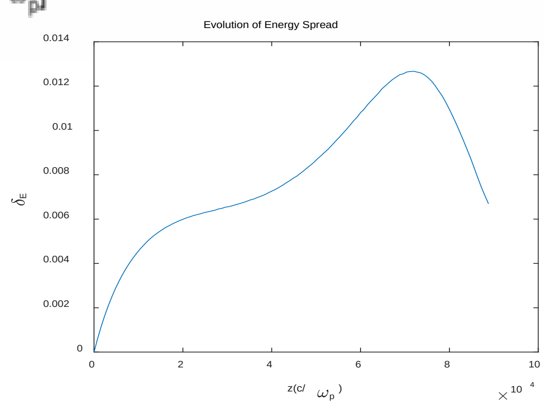
Plasma density $n_0(cm^{-3})$	5.15×10^{16}
Driver charge $Q_d(nC)$	6.47
Driver energy $E_d(GeV)$	10
Driver length $L_d(\mu m)$	285
Driver RMS size $\sigma_d(\mu m)$	10
Driver normalized emittance $\epsilon_{nd}(mm\ mrad)$	10
Trailor charge $Q_t(nC)$	1.25
Trailor energy $E_t(GeV)$	10
Trailor length $L_t(\mu m)$	35
Trailor RMS size $\sigma_t(\mu m)$	5
Trailor normalized emittance $\epsilon_{nt}(mm\ mrad)$	100



By Shiyu Zhou

HTR PWFA simulation (TR=3.55)



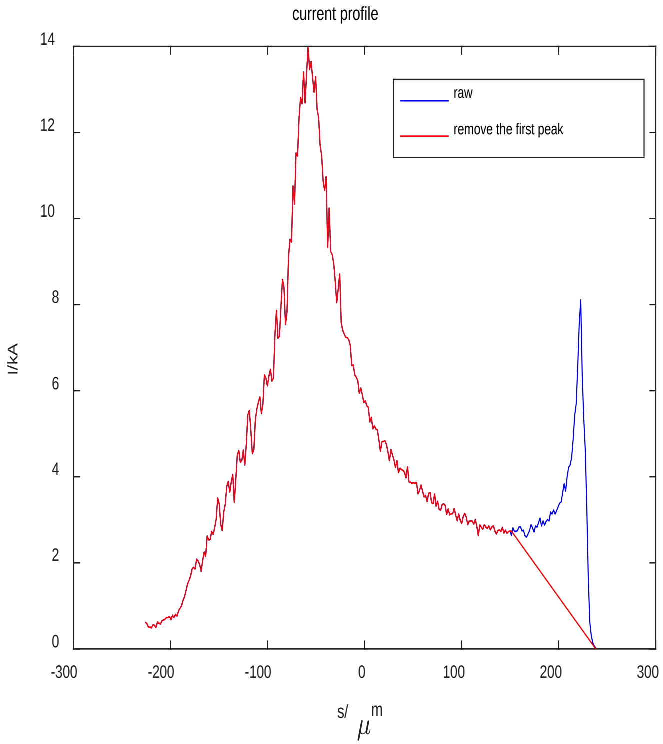


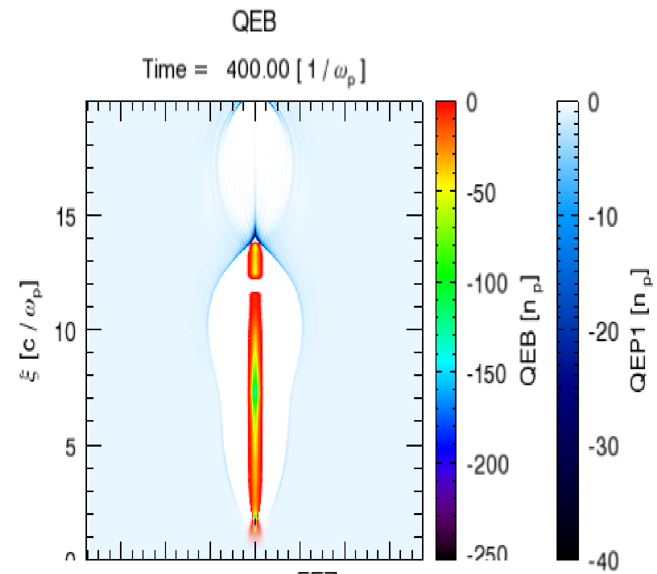
Output parameters

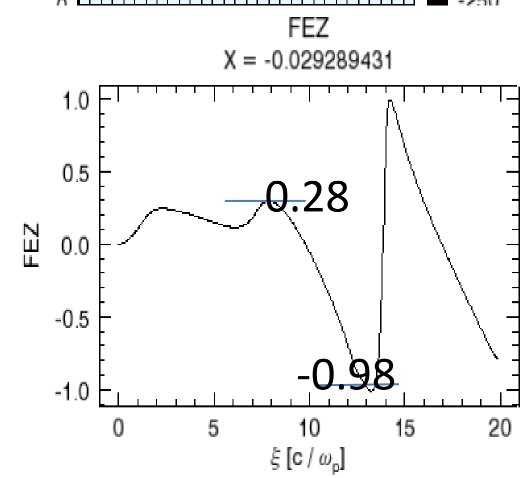
Trailor energy $E_t(GeV)$	45.5
Trailor normalized emittance $\epsilon_{nt}(mm\,mrad)$	98.9
TR	3.55
Energy spread $\delta_E(\%)$	0.7
Efficiency (driver -> trailor)	68.6%

Plasma length $\sim 1.9m$

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





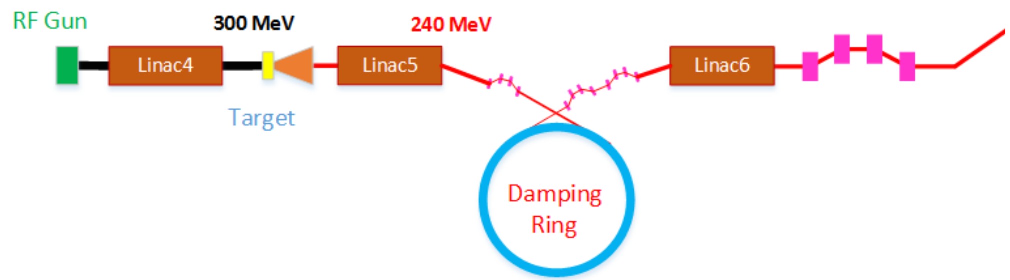


Simulation data by Zhen Wang of SINAP

$$\mathrm{TR} = 3.5$$

Positron generation

Damping ring	DR V1.0
Energy (MeV)	240
Circumference （m）	20
Bending radius (m)	1.7
B0 (T)	0.47
U0 (keV/turn)	0.17
Damping time x/y/z (ms)	185/185/93
δ0 (%)	0.016
ε0 (mm.mrad)	6
Nature σz (mm)	3
Extract σz (mm)	1.8
εinj (mm.mrad)	2400
εext x/y (mm.mrad)	819/815
δinj /δext (%)	1 /0.13
Storage time (ms)	100



RF parameters	
RF frequency (MHz)	500
RF voltage (MV)	0.8
Energy acceptance by RF(%)	1.8
harmonic	33

Lattice parameters	
FODO length (m)	1.2
Phase per cell	60°
Dipole length (m)	0.46
Dipole strength (T)	0.47
Quadrupole length (m)	0.11
Quadrupole strength (m^{-2})	15

By Dou Wang

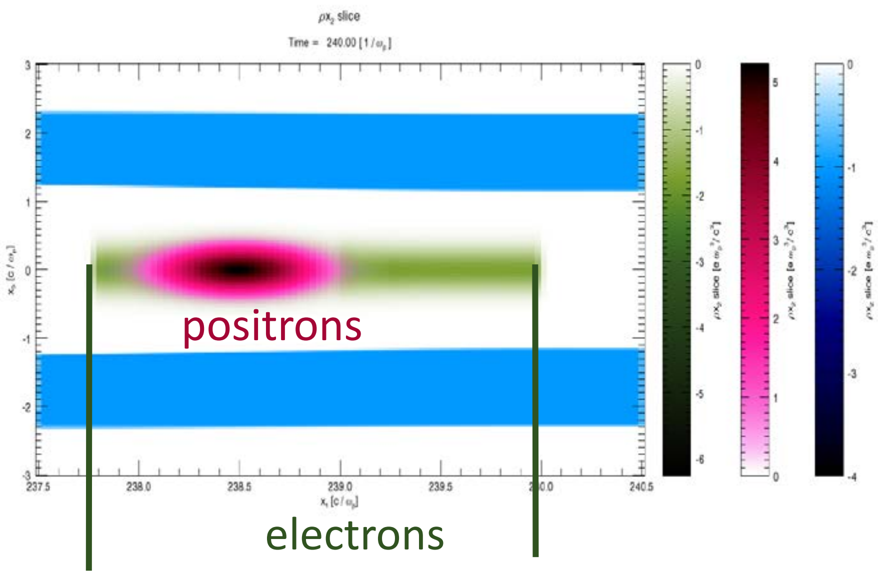
Positron compression

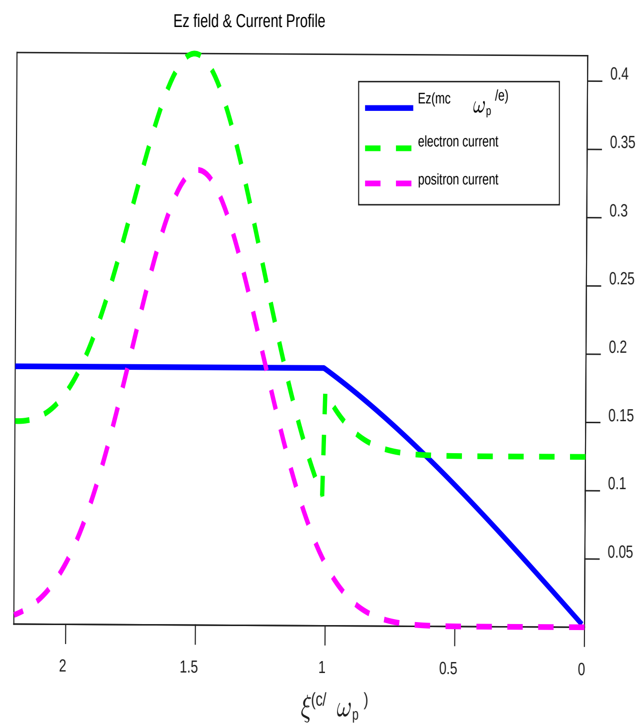
	BC I	BC II	BC III
Initial energy (MeV)	240	240	1300
δinj (%)	0.13	1.95	1.58
Initial σz (um)	1800	220	50
f_{RF} (MHz)	2856	2856	5712
Voltage(GV)	0.14	5.0	36
ϕ_{RF} (度)	90	77.8	86.6
R_{56} (mm)	92	13.9	2.5
Final energy(MeV)	240	1300	3400
δext (%)	1.95	1.58	2.0
final σz (um)	220	50	15

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

Positron Acceleration in a Hollow Plasma Channel

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





Current profile of e-/e+

By Shiyu Zhou

Input parameters

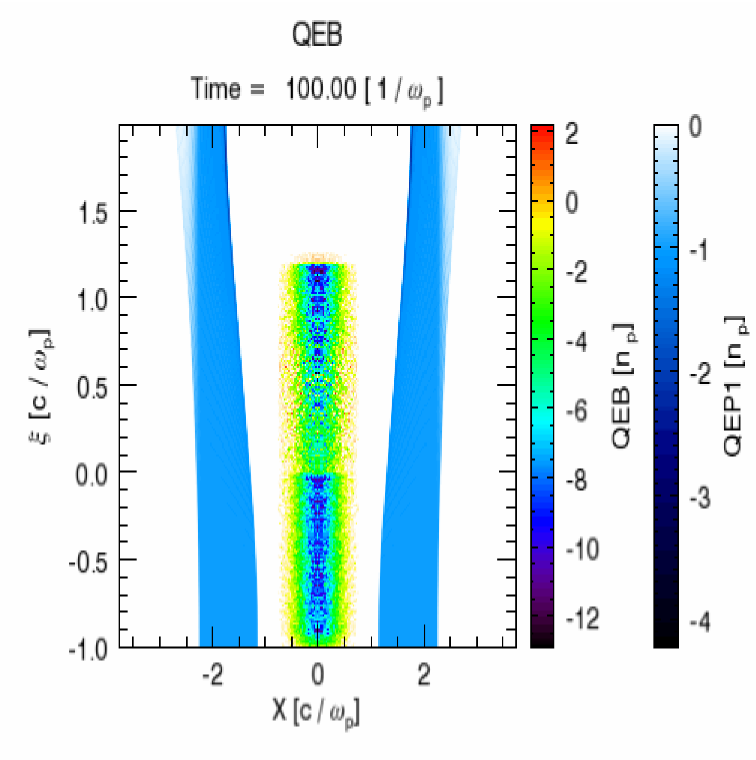
Plasma density $n_0(cm^{-3})$	1.77×10^{16}
Channel inner radius $r_1(\mu m)$	45
Channel out radius $r_2(\mu m)$	90
Bunches	
Driver charge $Q_d(nC)$	2.13
Driver energy $E_d(GeV)$	45.5
Driver length $L_d(\mu m)$	88
Driver RMS size $\sigma_d(\mu m)$	10
Driver normalized emittance $\epsilon_{nd}(mm\ mrad)$	100
Trailor charge $Q_t(nC)$	1
Trailor energy $E_t(GeV)$	0.3
Trailor length $L_{t-rms}(\mu m)$	10
Trailor RMS size $\sigma_t(\mu m)$	10
Trailor normalized emittance $\epsilon_{nt}(mm\ mrad)$	100

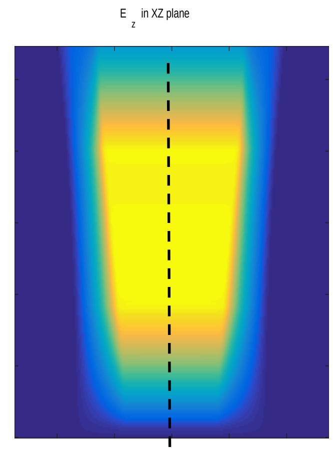
Output parameters

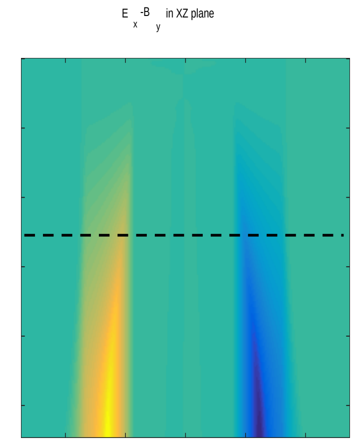
Trailor energy $E_t(GeV)$	45.5
Trailor normalized emittance $\epsilon_{nt}(mm\ mrad)$	100
TR	1
Energy spread $\delta_E(\%)$	1.3
Efficiency (driver -> trailor)	46.9%

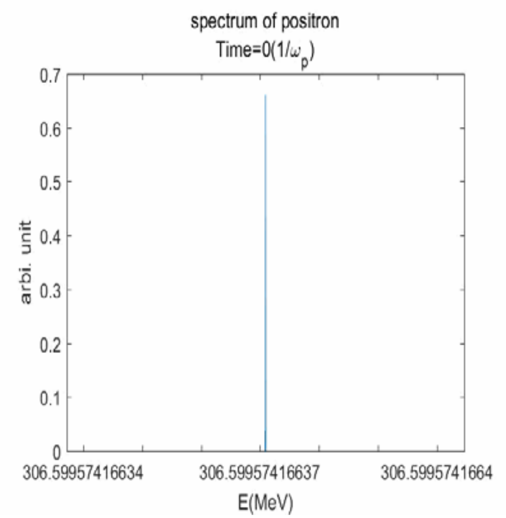
Plasma length $\sim 22m$

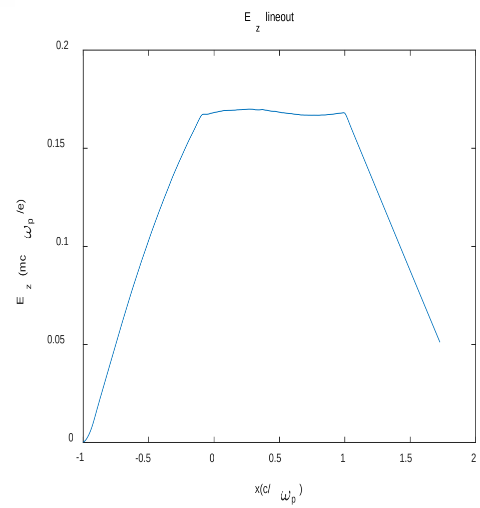
Fields Structure

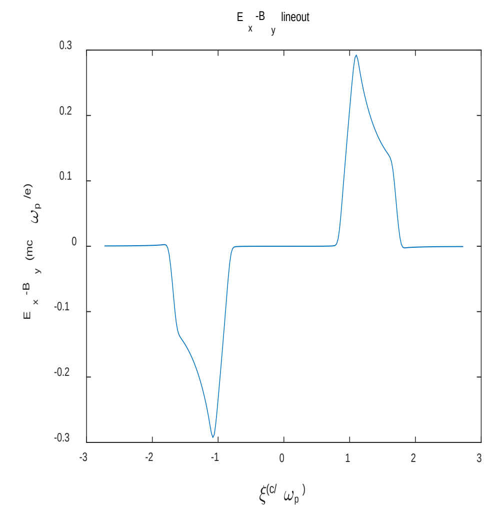








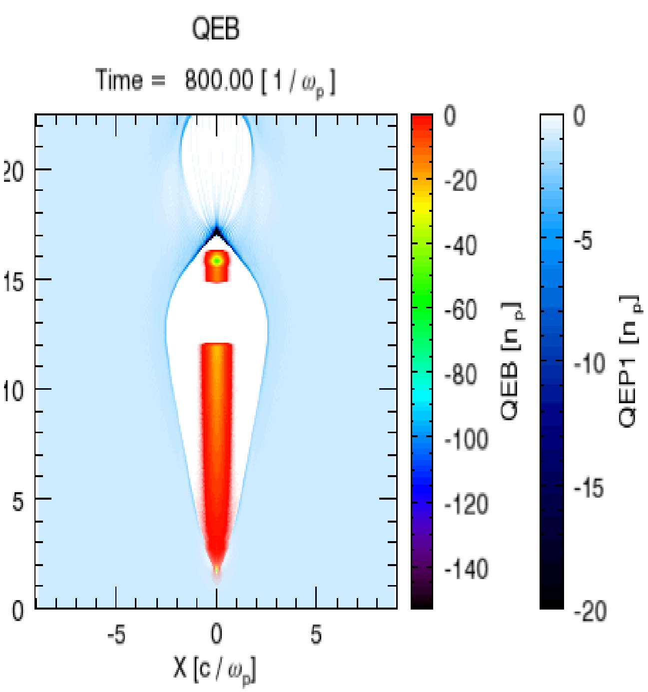




Electron driver/trailer parameters for e+ acceleration

Input parameters

Plasma density $n_0(cm^{-3})$	$1.44{\times}10^{16}$
Driver charge $Q_d(nC)$	12.4
Driver energy $E_d(GeV)$	10
Driver length $L_d(\mu m)$	540
Driver RMS size $\sigma_d(\mu m)$	20
Driver normalized emittance $\epsilon_{nd}(mm\,mrad)$	100
Trailor charge $Q_t(nC)$	2
Trailor energy $E_t(GeV)$	10
Trailor length $L_t(\mu m)$	88
Trailor RMS size $\sigma_t(\mu m)$	10
Trailor normalized emittance $\epsilon_{nt}(mm\,mrad)$	200



TR~3.5

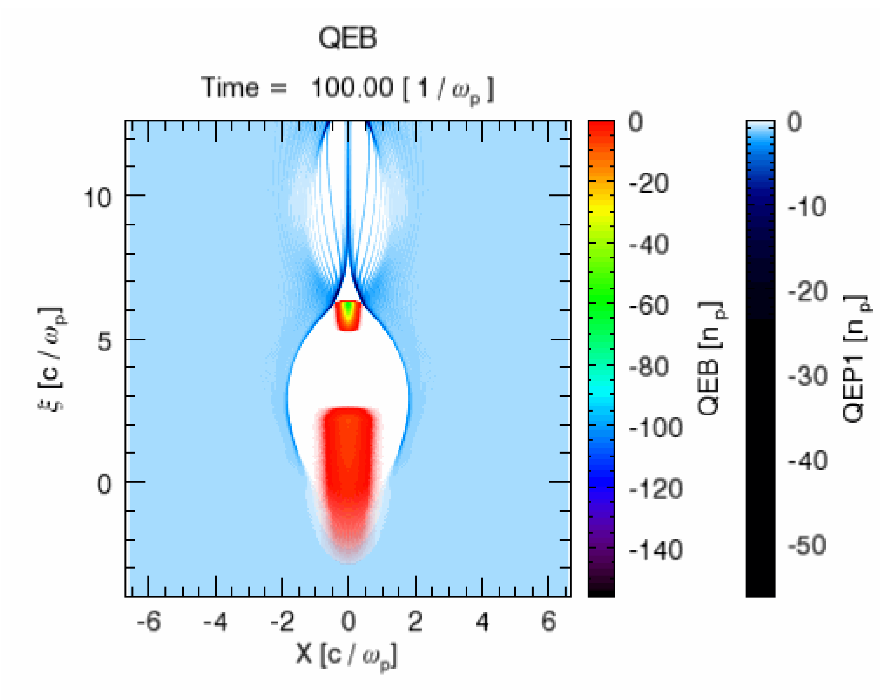
Cascaded HTR PWFA

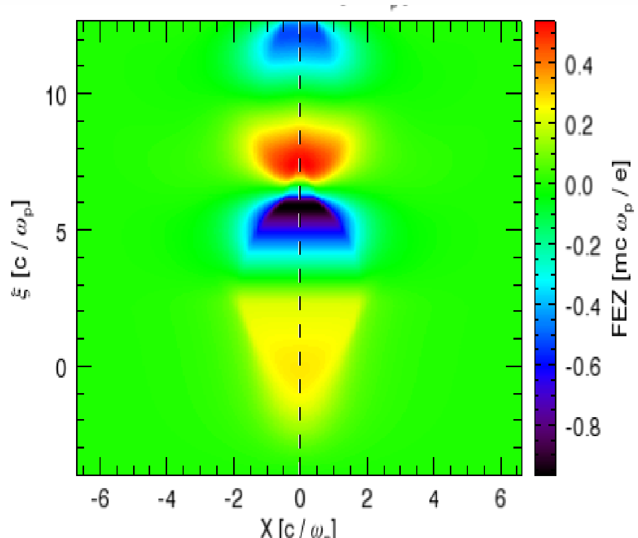
- **The 1st stage**
  - Two shaped bunches (**5ps 25nC, 1ps 5nC**)
  - TR=2 or 3
  - Efficiency (**60%**)
- **The 2nd stage**
  - Controlled injection for e (**200fs 1nC or 2nC**)
  - TR=2 or 3
  - Single stage efficiency (**60%**)
  - Overall **TR=(1+TR1)*TR2**
- Overall efficiency **Q3(1+TR1)*TR2/(Q1+Q2)=40%**
- **The positron stage**
  - Combining e+ with e- (**200fs 1nC**)
  - TR=1 Single stage efficiency (**~50%**)
  - Overall efficiency for positron **20%**

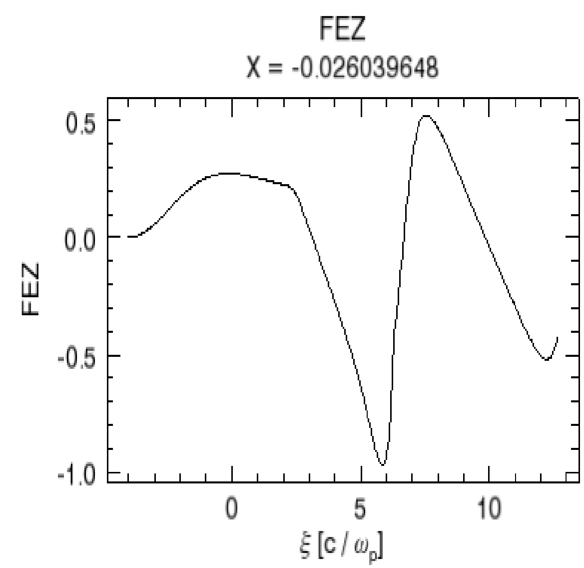
Electron Acceleration Stage (I and II)

Parameters of Stage I

Driver pulse	5ps
Driver charge Q1	25nC
Driver energy	2GeV
Trailer pulse	0.5ps
Trailor charge Q2	5nC
Trailor energy	2GeV
Final energy	8GeV
Average TR	3
Efficiency	~60%







Summary

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

- e-/e+ acceleration to 100GeV 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!