4th European Advanced Accelerator Concepts Workshop

External Injection experiment: first accelerated beam

Jianfei Hua

Tsinghua University

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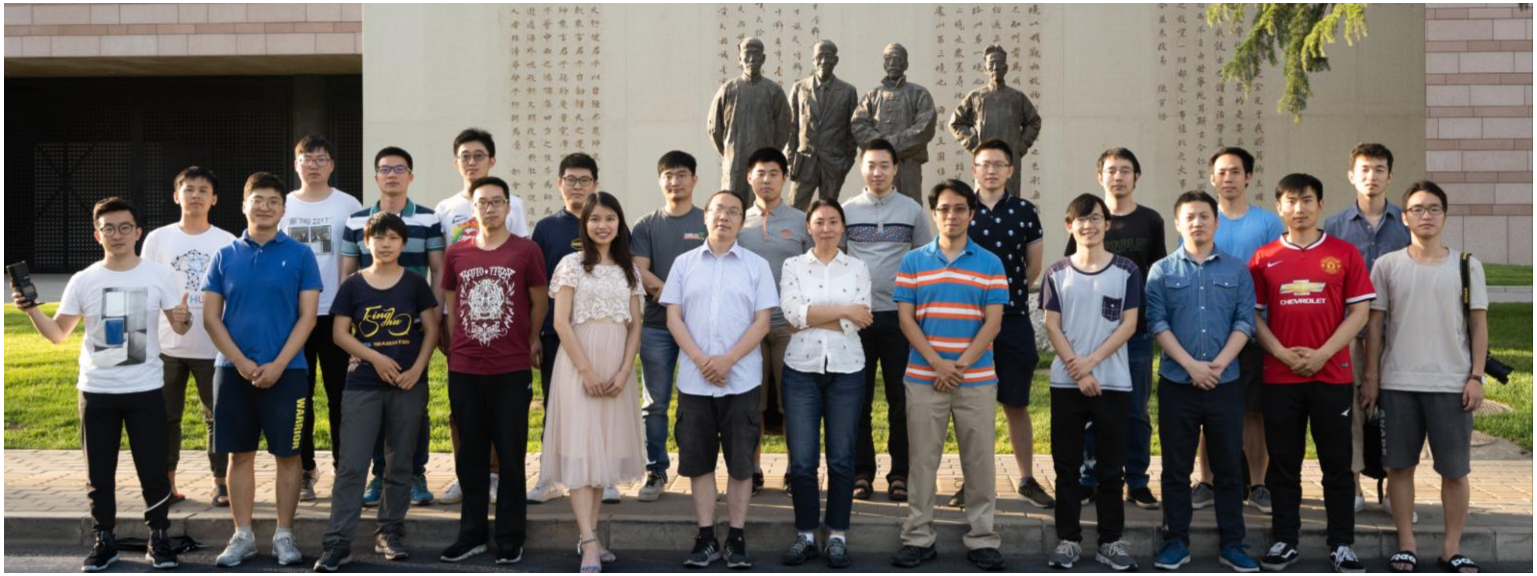
Acknowledgements

Laboratory of Laser Plasma Physics and Advanced Accelerator Technology



Collaborators

Zheng Zhou, Yingchao Du, Lixin Yan, Jiaru Shi, Chuanxiang Tang

Hsu-Hsin Chu and Jypyng Wang

UCLA Weiming An, Chaojie Zhang, Fei Li, Zan Nie, Warren Mori, Chan Joshi

SINAP Zhen Wang, Xingtao Wang, Bo Liu, Zhentang Zhao

SLAC Xinlu Xu, Mark Hogan

Dou Wang, Dazhang Li, Jie Gao

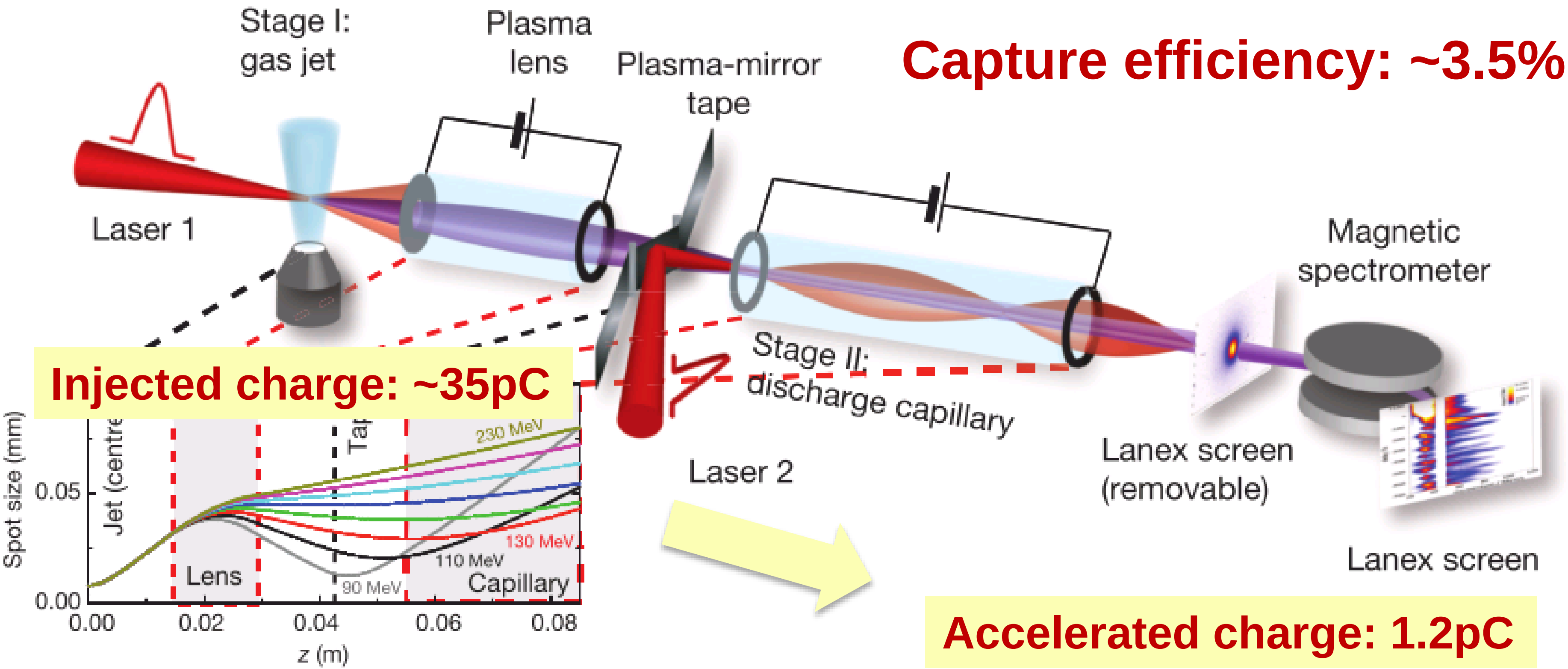
Yang Wan, Victor Malka

Outline

- External injection from a Linac into a LWFA with ~100% capture efficiency
- Plasma dechriper to achieve 0.1% energy spread
- Ultra-compact turnkey laser development
- High energy plasma based injector for CEPC
- Summary

Two milestones for external injection

Capture efficiency: ~3.5%

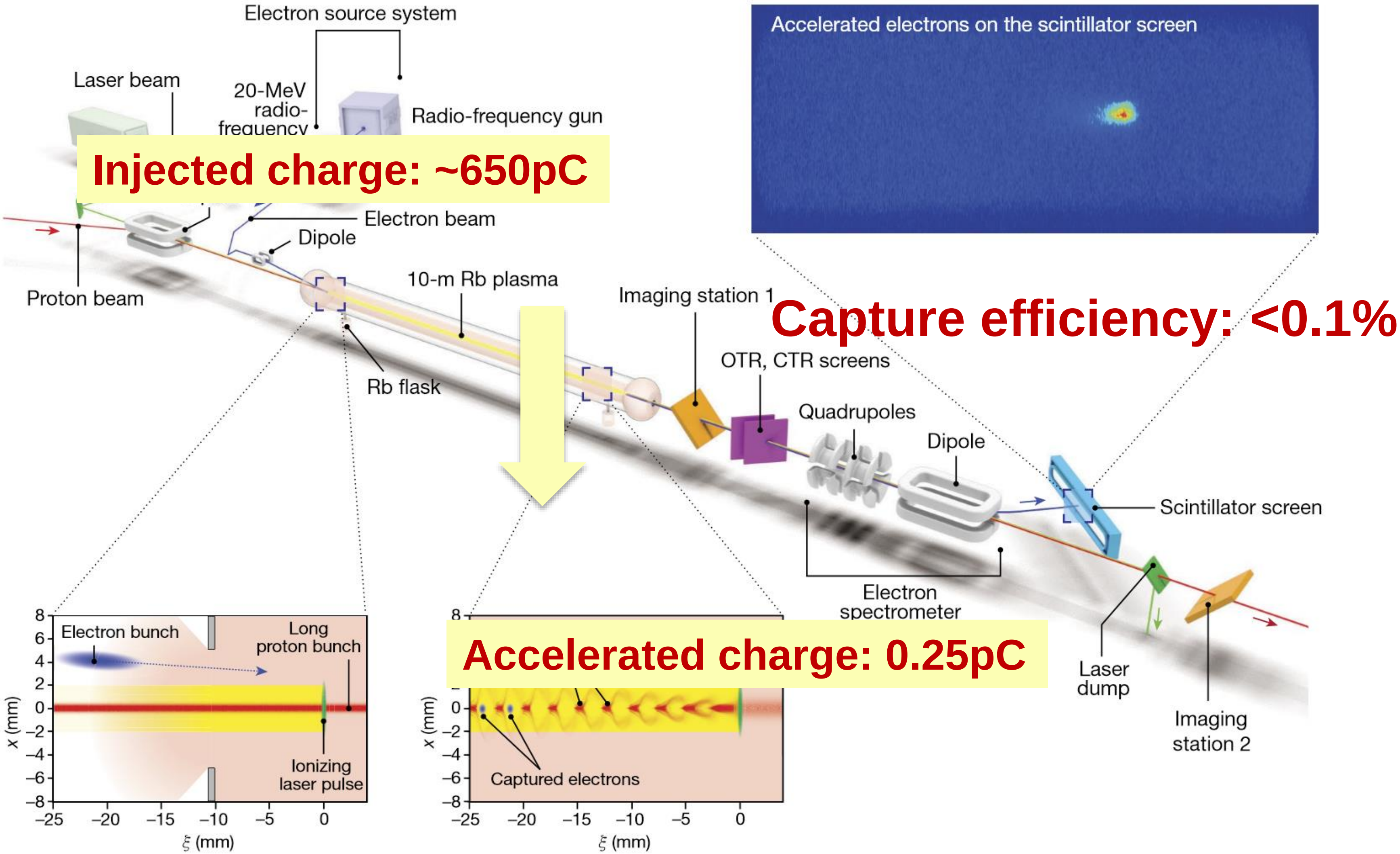


Injected charge: ~35pC

Accelerated charge: 1.2pC

S. Steinke, et al., “***Multistage coupling of independent laser-plasma accelerators***”, Nature, 530: 190, 2016

Two milestones for external injection



E. Adli, et al., "***Acceleration of electrons in the plasma wakefield of a proton bunch***", Nature, 561: 363, 2018

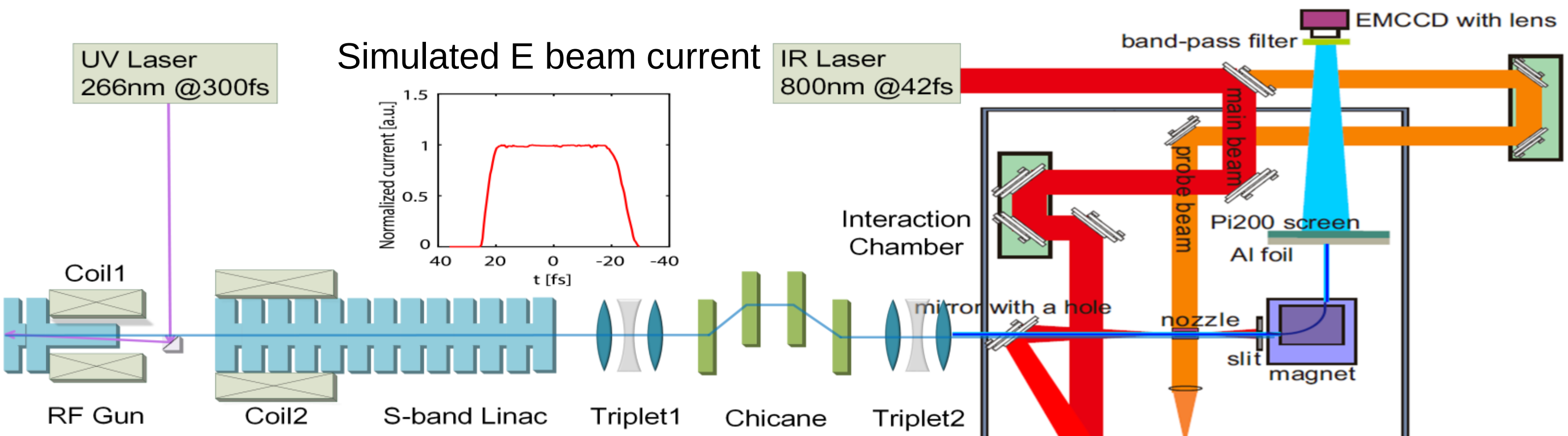
Demonstration of external injection

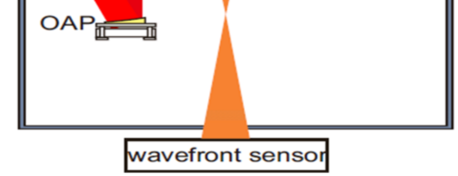
- External injection from a Linac to a LWFA
- Subsequent acceleration
- ~100% capture efficiency

Key challenges

- ✓ Ultrashort beam generation ($<\lambda_p$) ~13fs
- ✓ Size matching (tightly focused E beam $\sim w_0$) ~20µm
- ✓ Synchronization between beam and laser ($<\lambda_p$) ~100fs
- ✓ Phase space matching
- ✓ Vacuum isolation between Linac and LWFA
- ✓ Robust plasma source based on laser ionization

Experimental layout for external injection



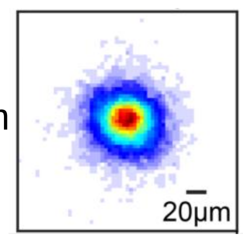


Electron	
Trans. size	σ_r~20μm
Bunch length	σ_z~13fs
Charge	20fC
Energy	31.3MeV

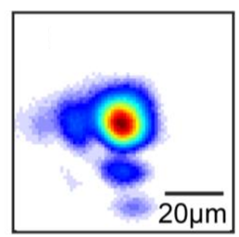
Laser	
Enclosed Power	9TW
Duration	40fs
Focus size(FWHM)	12μm

Plasma	
Density	10^{17} -10^{18} cm^{-3}
Length	6mm

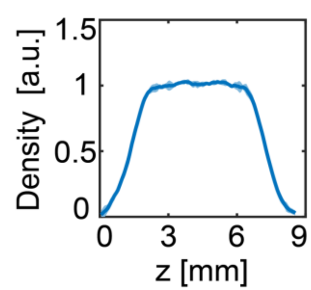
E. beam

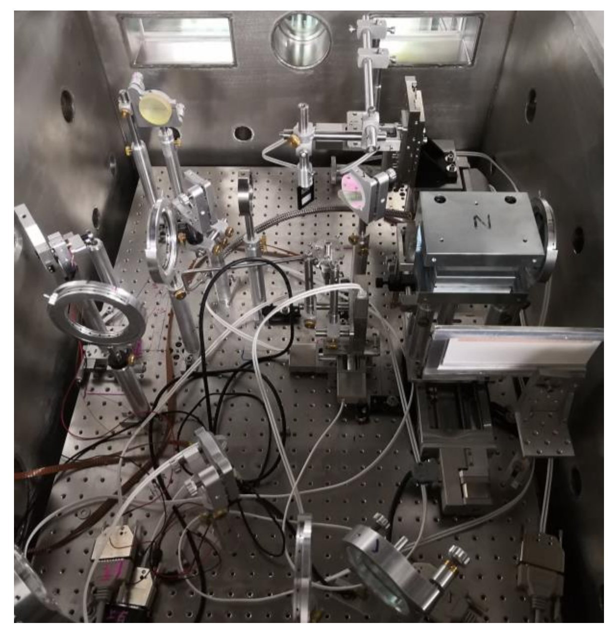


Laser



Plasma





Achievement of external injection acceleration from a Linac to a LWFA

accel. phase

unpublished

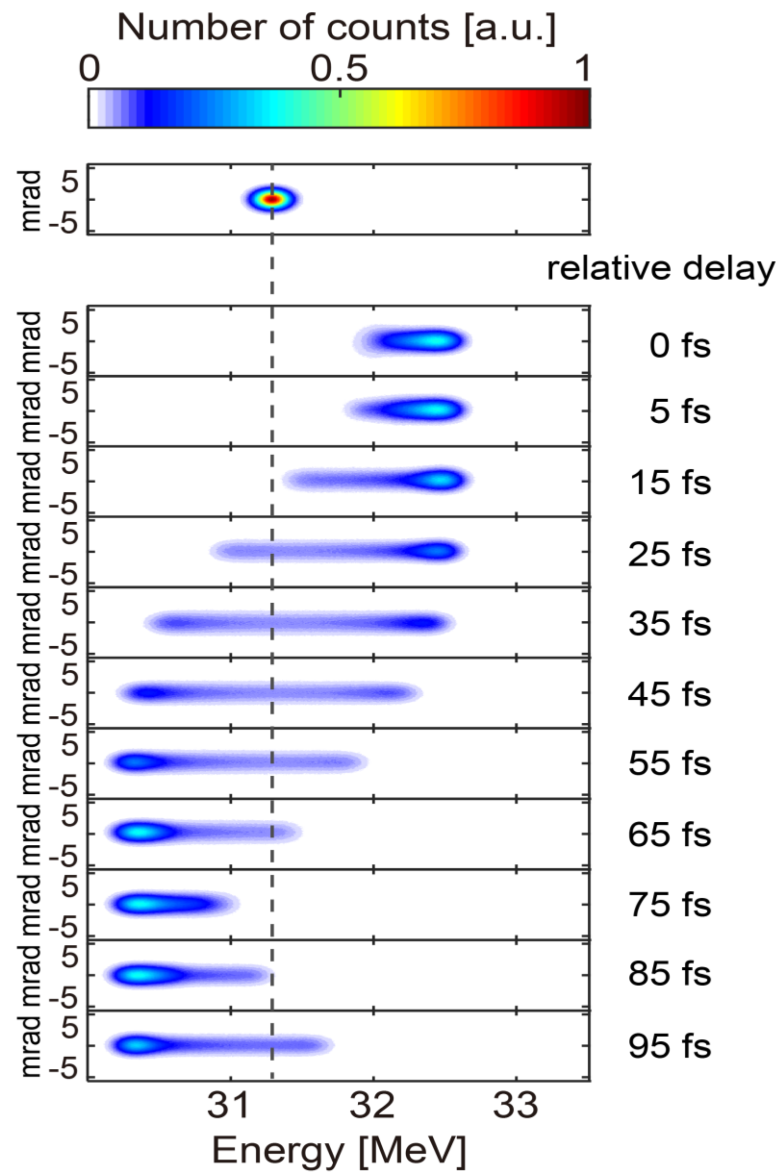
Jitter：~100fs（rms）

Wavelength: 140fs

Focus location：
z_f=-4.5mm

Density：$6 \times 10^{17} cm^{-3}$

decel. phase



Achievement of external injection acceleration from a Linac to a LWFA

Gain: 1.11MeV(~1.5MeV) average(max.)

accel. phase

0.22MeV
(FWHM)

0.36MeV
(FWHM)

unpublished

Jitter：~100fs（rms）

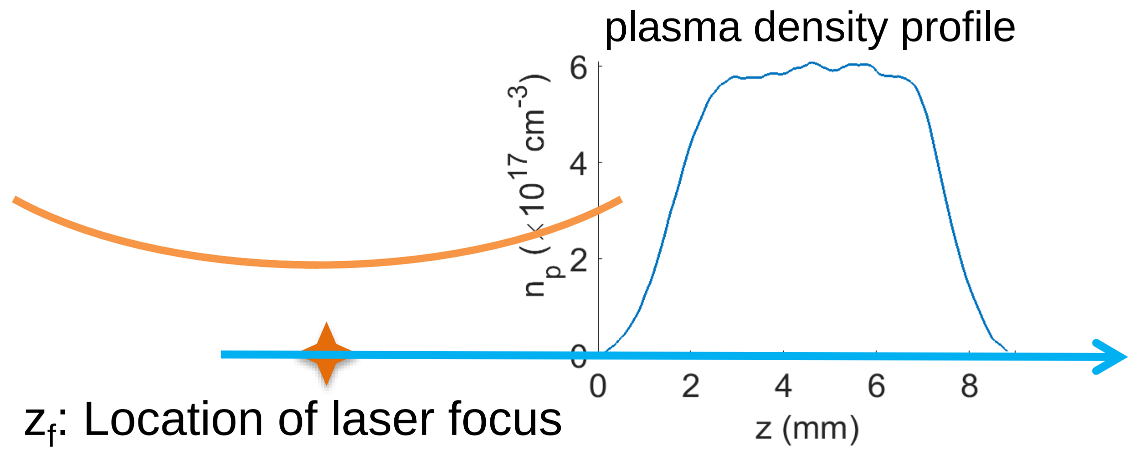
Wavelength: 140fs

Focus location：
z_f=-4.5mm

Density：6×10^{17}cm^{-3}

decel. phase

Two crucial parameters for gain and efficiency



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Focus location:
z_f=-4.5mm

Density: 6×10^{17}cm^{-3}

Effect of laser focus location

unpublished

z_f = -3.5 mm
1.45MeV

z_f = -4.5 mm
1.11MeV

z_f = -5.5 mm
0.77MeV

$$E_z \propto \boxed{a_0^2} k_p^2 \exp(-2r^2/w^2)$$

Location of focus z_f $\downarrow$
Beam size $\downarrow$
a_0 $\uparrow$ Energy gain $\uparrow$

The plasma density dependent energy gain

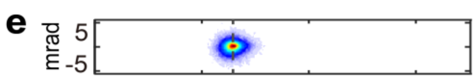
unpublished

$6 \times 10^{17} cm^{-3}$

0.77 MeV

$2 \times 10^{17} cm^{-3}$

0.26 MeV



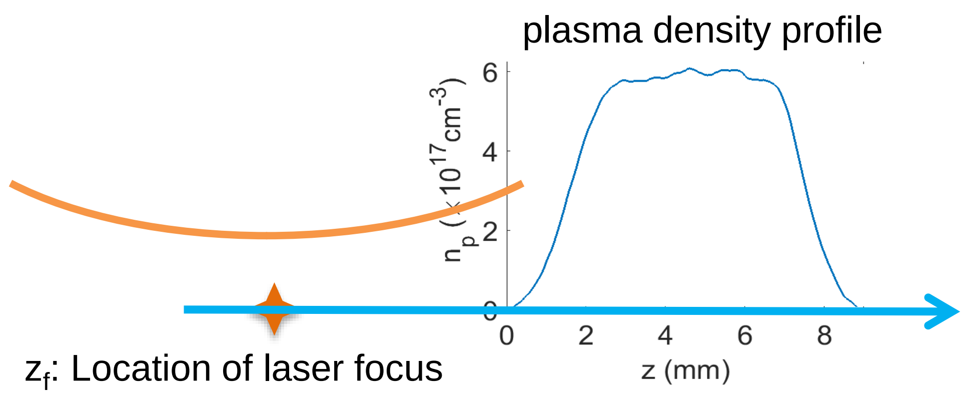
Plasma off

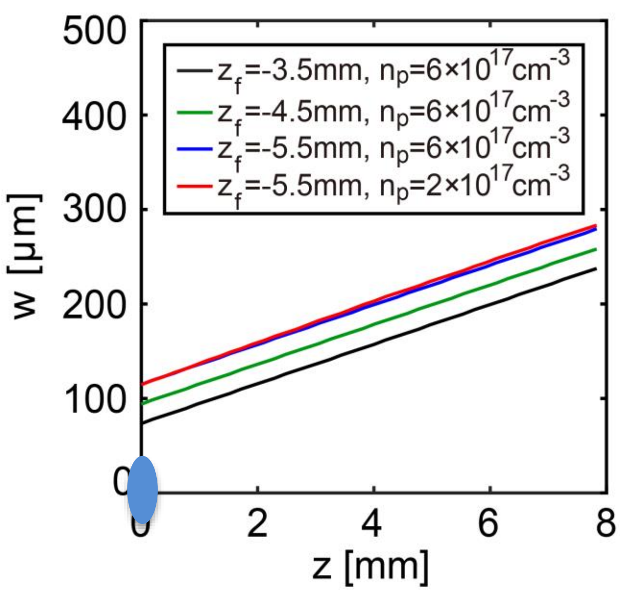
$$E_z \propto a_0^2 \boxed{k_p^2} \exp(-2r^2/w^2)$$

- Energy gain $\propto$ n_p
- Lower density: Wavelength ↑ Energy spread ↓

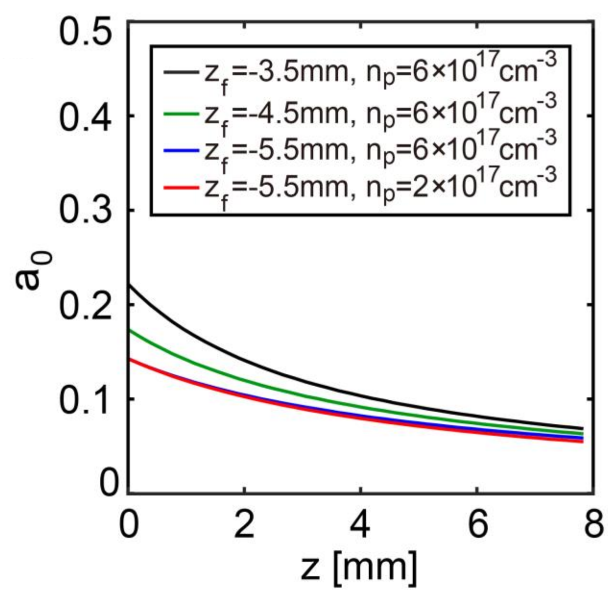
How to improve capture efficiency?

- Size matching between wakefield and electron beam
  - ✓ Tight beam focusing
  - ✓ Large laser spot size





Laser spot size

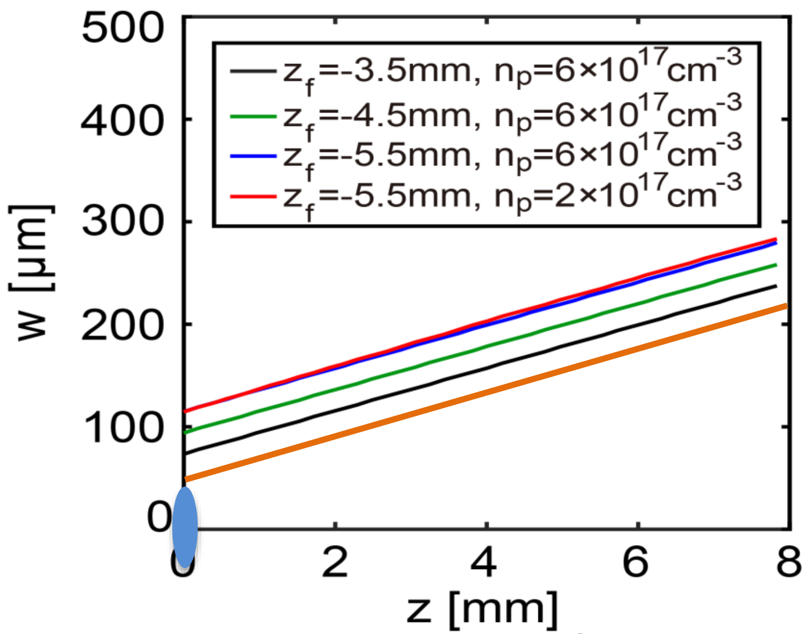


Vector potential

Non-optimized capture efficiency

Low capture efficiency

unpublished



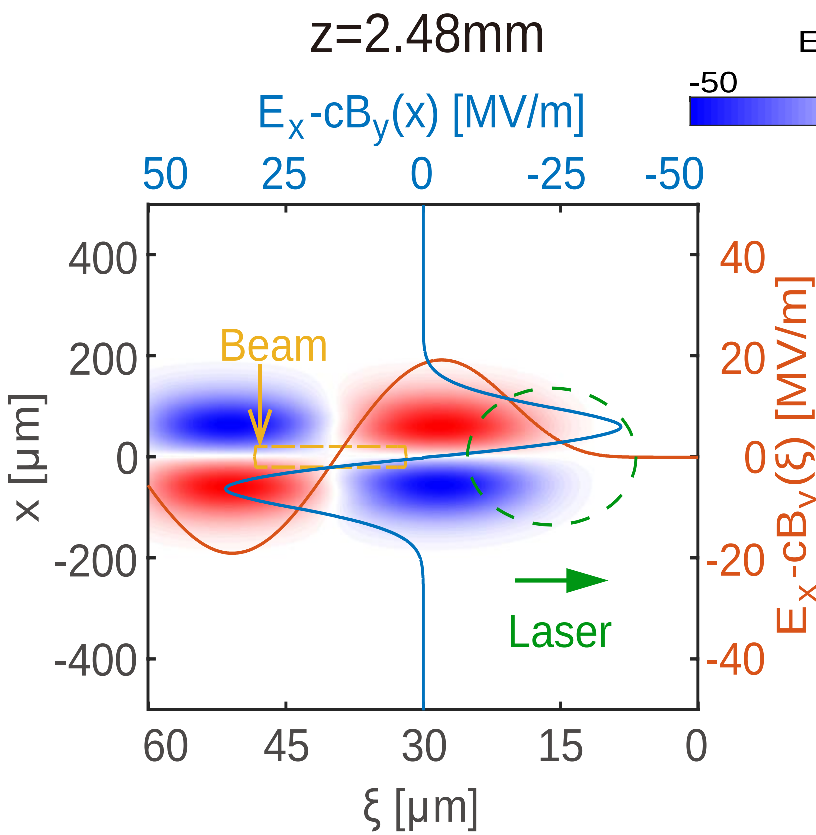
Laser spot size

z_f = -1.5 mm, n_p=6 X10^{17} cm^{-3}

Phase space dynamics

Transverse wakefield：

$$E_r - B_\theta \propto (4a_0^2 k_p r/w^2)\exp(-2r^2/w^2)\sin(k_p\xi)$$



z_f=-3.5mm, Density=6 × 10^{17}cm^{-3}

- Linear in r in the beam region

  ☺ Preserve the slice emittance

- Rotation of slice phase ellipses

  ☹ Projected emittance growth

Emittance precompensation by up-ramp

Up-ramp:

$$\partial(E_r - cB_\theta)/\partial\xi > 0$$

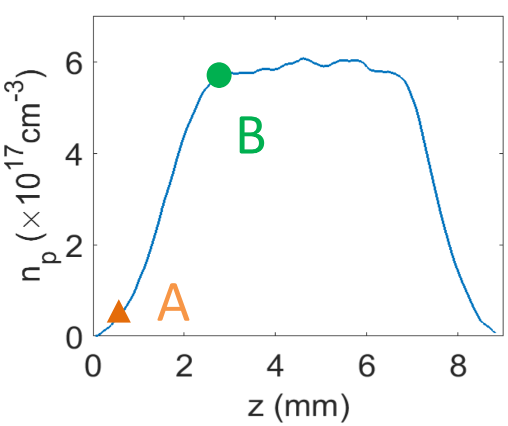
Plasma plateau:

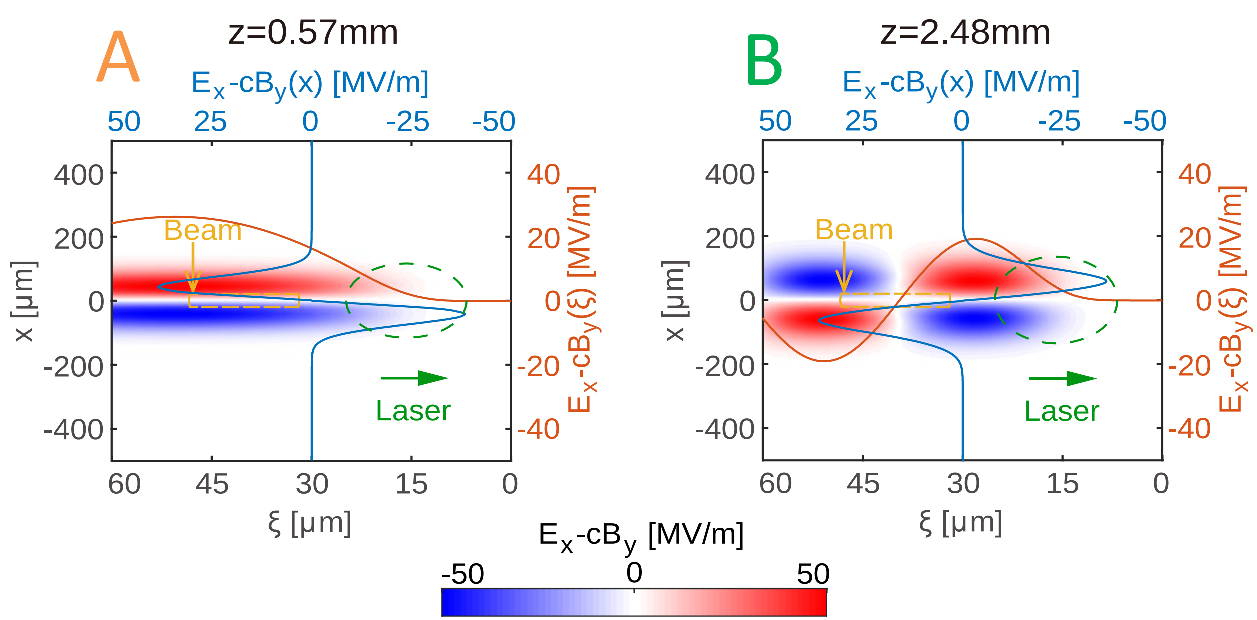
$$\partial(E_r - cB_\theta)/\partial\xi < 0$$

Reverse the rotation direction of transverse phase space

Compensated by the long plasma up-ramp for the accumulated phase differences in the plasma plateau

Plasma structure





Emittance evolutions with or without up-ramp

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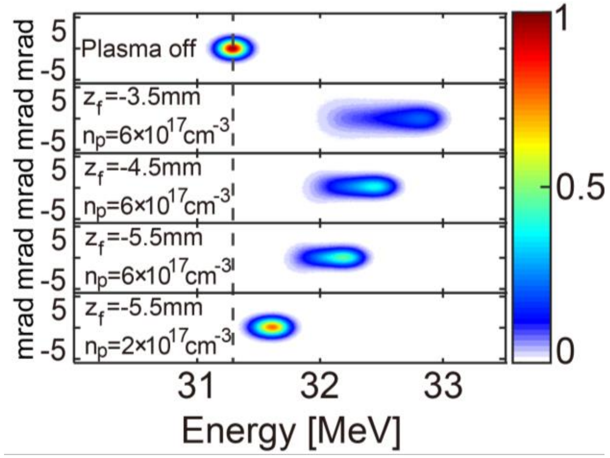
3D PIC simulation for high efficiency acceleration

unpublished



Simulated laser-excited longitudinal wakefields

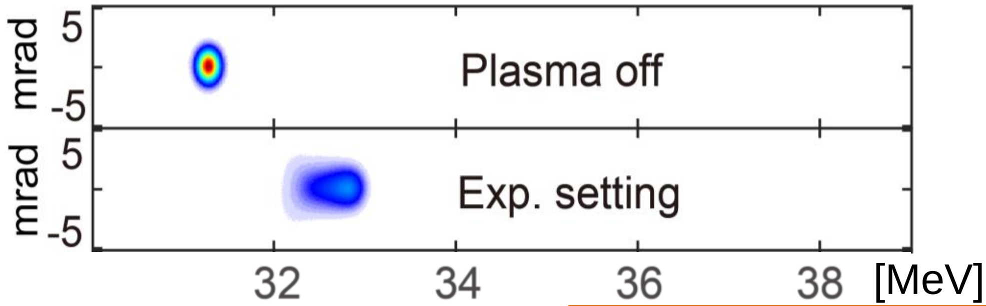
Feasibility of high-charge external-injected beam into a LWFA

Q=20 fC → Q=6 pC,13fs

beam excited wakefield ~ laser excited wakefield

unpublished

Feasibility of high-energy gain



z_f=-3.5mm(w_0=75μm)

n_p=6×10^{17}cm^{-3}

9TW@6mm

1.5MeV gain
(~250MV/m)

Laser:
200TW, 40fs, a0=2.2
w0=35μm

Plasma:
2×10^{17}cm^{-3}
~20cm plateau

E-beam:
10fs, 20pC, σ_r=3.6μm
1mm mrad

25MeV

Grad: ~33GV/m

4.7GeV

unpublished

Outline

- External injection from a Linac into a LWFA with ~100% capture efficiency
- **Plasma dechriper to achieve 0.1% energy spread**
  - Experimental demonstration using uniform plasma dechriper
  - A near ideal dechirper to achieve <0.1% energy spread using hollow channel plasma
- Ultra-compact turnkey laser development
- High energy plasma based injector for CEPC
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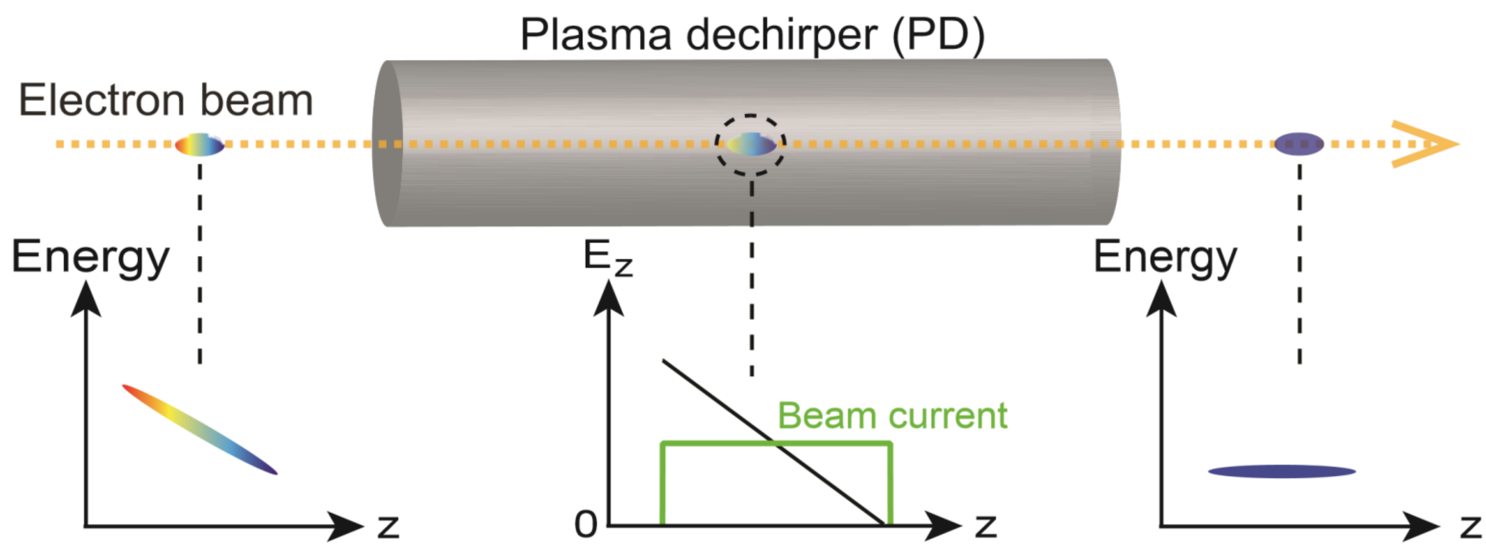
Energy chirp dominated energy spread

- Energy spread ~1% > the requirement of ~0.1% for the applications of FELs and colliders
- Relatively large acceleration phase span leads to large energy chirp (positive linear).



Linear positive chirp   On-axis longitudinal wakefield   Energy chirp reduction

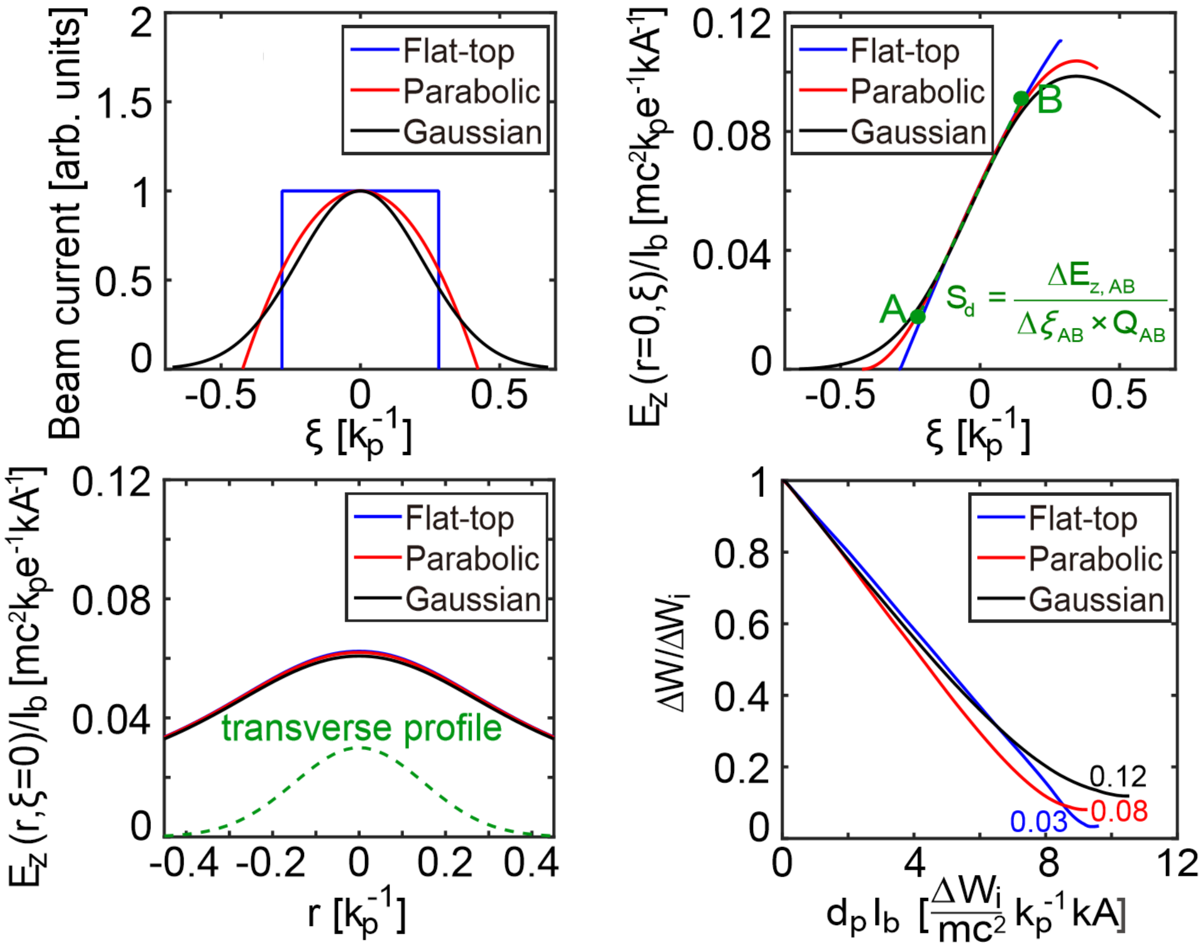
Y. P. Wu, et al., Proceedings of IPAC 2017,1258 (2017)
Y. P. Wu, et al., PRL, 122 :204804, 2019

PD effect for different beam current profiles

Dechirping strength:

$$S_d = \frac{\Delta E_{z,\mathrm{AB}}}{\Delta\xi_{\mathrm{AB}} \times Q_{\mathrm{AB}}}$$

S. Antipov, et al., PRL, 112, 114801 (2014)



Dechirping factor:

33.3 (flat-top)

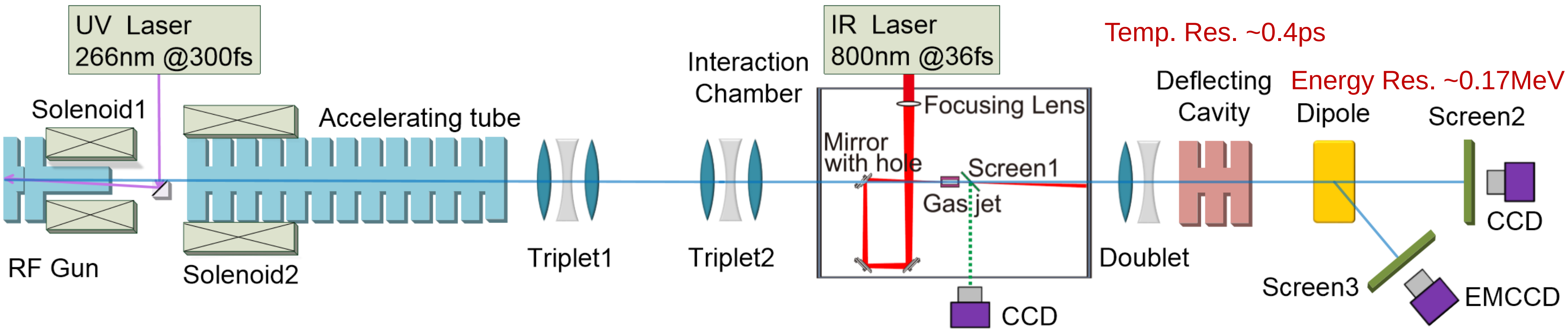
12.5 (parabolic)

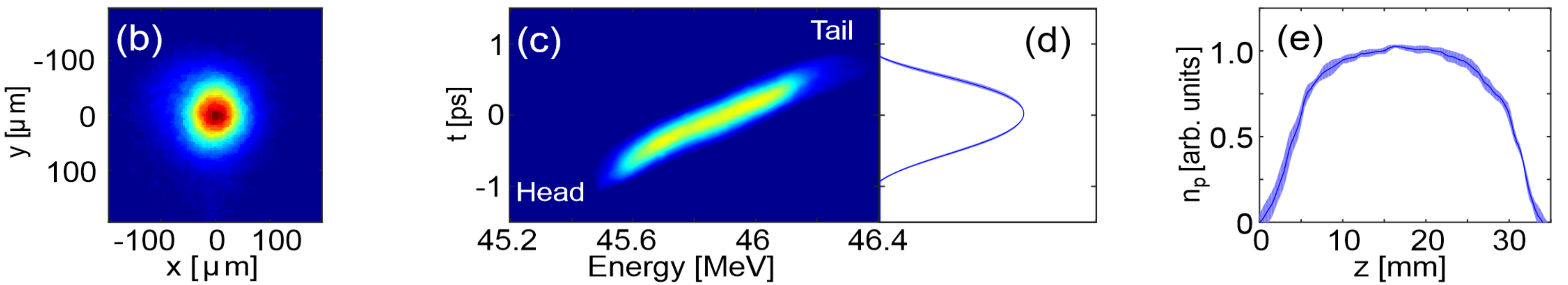
8.3 (Gaussian)

Energy spread reduction:

The complex interplay and trade-off among the linear chirp reduction, the nonlinear chirp increase and the slice energy spread growth.

Plasma dechirper experimental layout



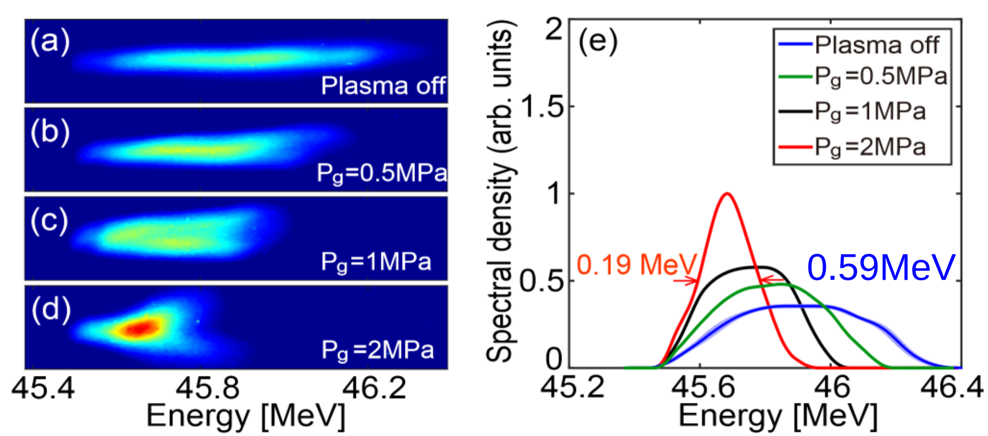


Beam spot

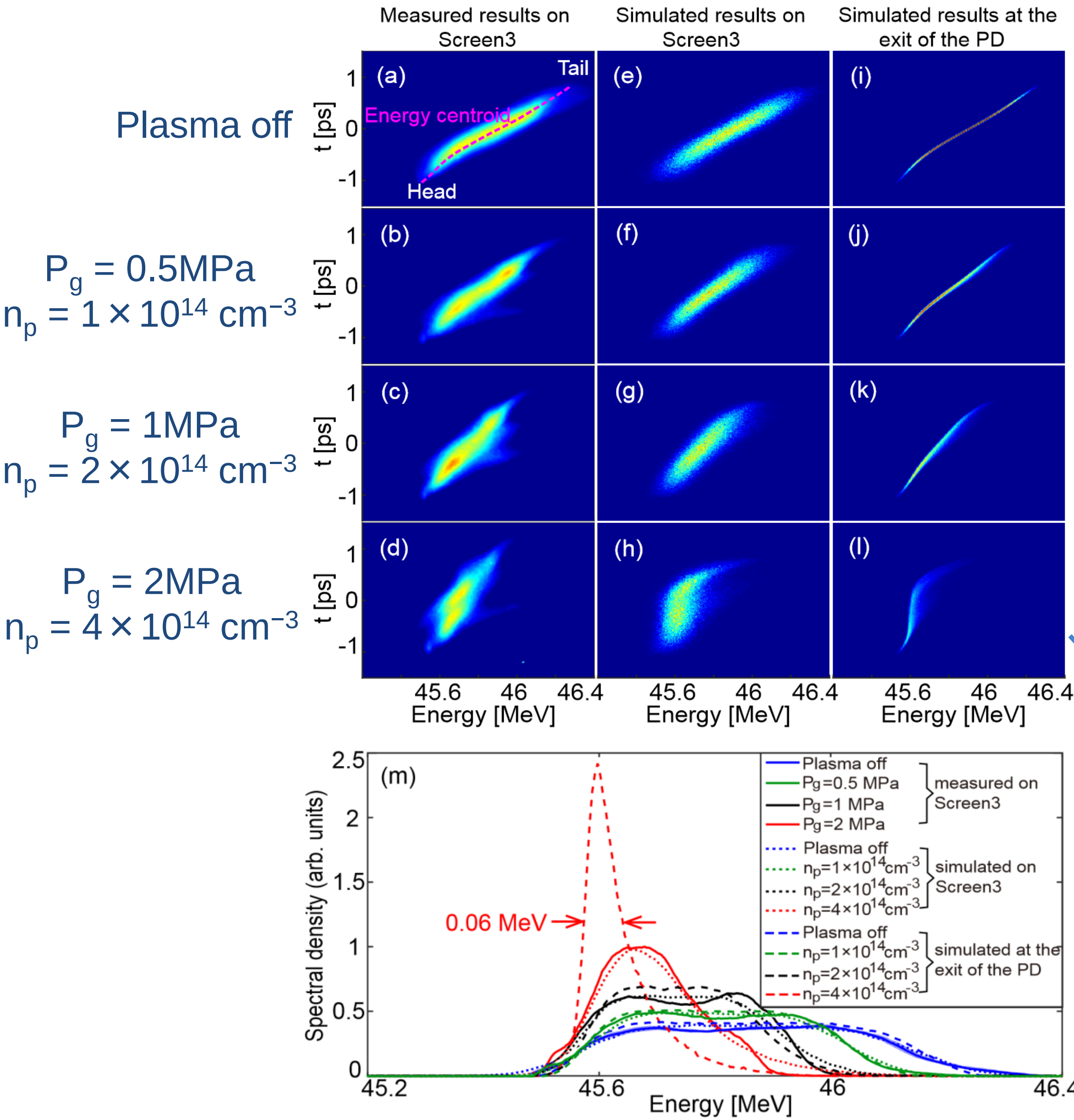
Phase space and parabolic current profile

Density profile

Electron	Trans. size	σ_r~40μm
	Bunch length	1.1ps (FWHM)
	Charge	40pC
	Energy	46MeV
Plasma	Density	10^{14} -10^{15} cm^{-3}
	Length	30mm



Phase space dynamics for energy spread reduction



0.59MeV(1.28%)

Low plasma density

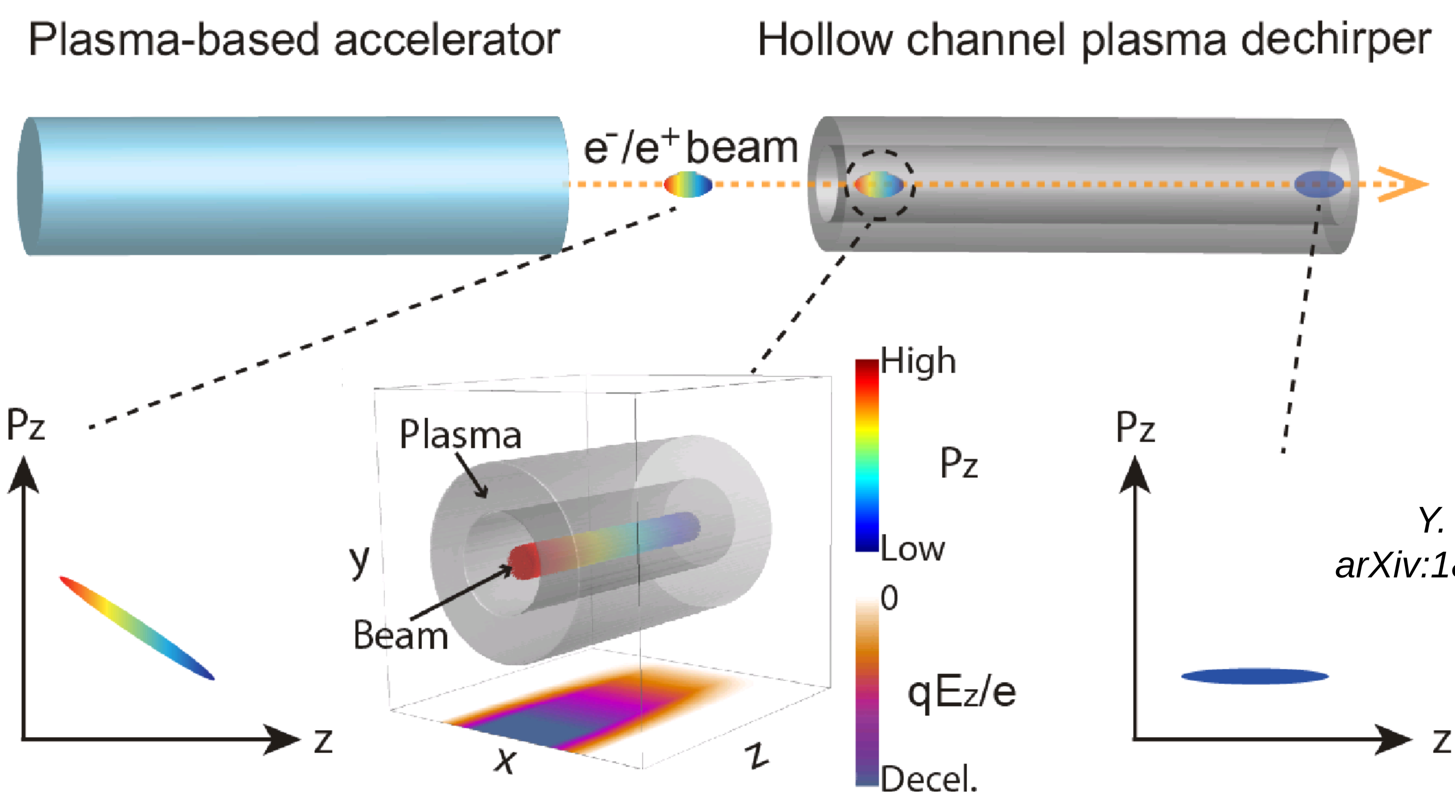
The comparisons use only one parameter to closely match three longitudinal phase spaces and integrated energy spectra.

0.06MeV(0.13%)

$S_d \approx 1$ (MV/m)/(mm pC)

Solution for reducing emittance growth: a hollow channel plasma dechirper

- Transversely uniform E_z ➡ negligible slice energy spread increase
- Zero transverse focusing force ➡ negligible emittance growth
- **Works well for both electron and positron beams**

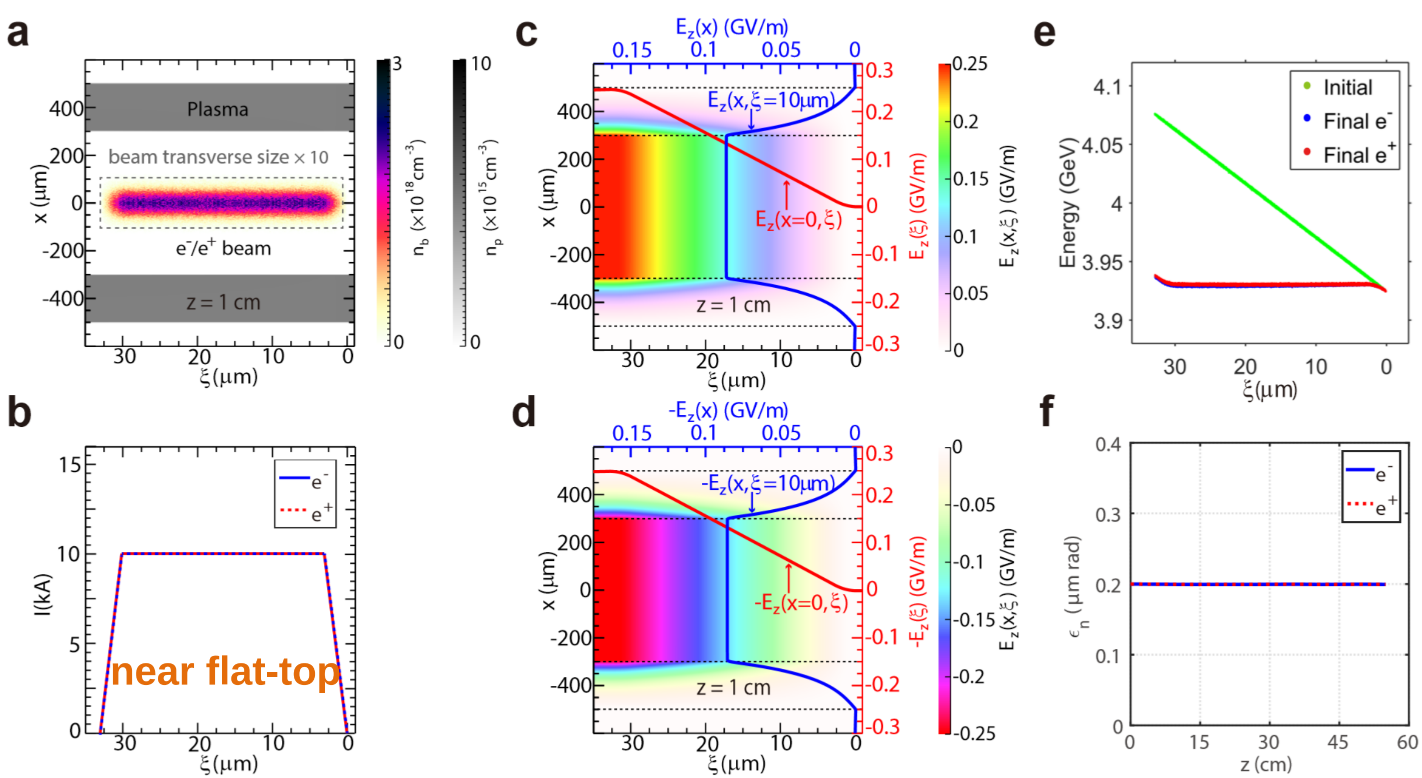


Y. P. Wu, et al., arXiv:1805.07031v3

PIC Simulation for hollow channel dechirper

Electron/ Positron	Energy	4GeV
	Energy chirp	40MeV (rms)
	Slice energy spread	0.4MeV
	Peak current	10kA
	Pulse duration	30μm (100fs)
	Transverse size	σ_r=4μm

Plasma	Density	5.0×10^{15}cm^{-3}
	Length	~55cm
	Inner radius	a=300μm
	Outer radius	b=500μm



40MeV(1%)

e^-: 0.76MeV 0.02%

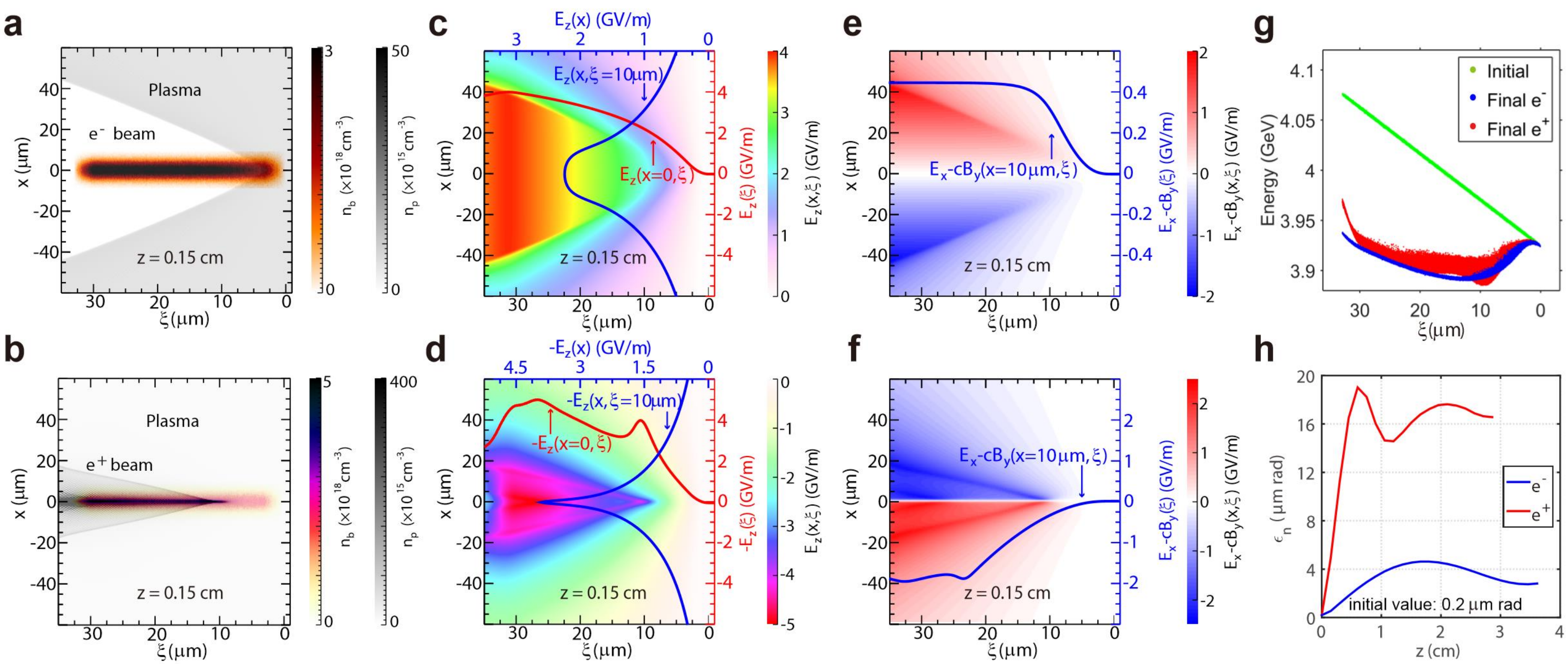
e^+: 0.72MeV 0.02%

PIC Simulation for uniform plasma dechirper

- **The longitudinal nonlinearity and the transverse nonuniformity of E_z**

40MeV(1%) → e−: 11.58MeV(0.29%) / e+: 12.49MeV(0.31%)

15 (e^-)/17 (e^+) times larger



- **The transverse wakefield depends on the longitudinal position**

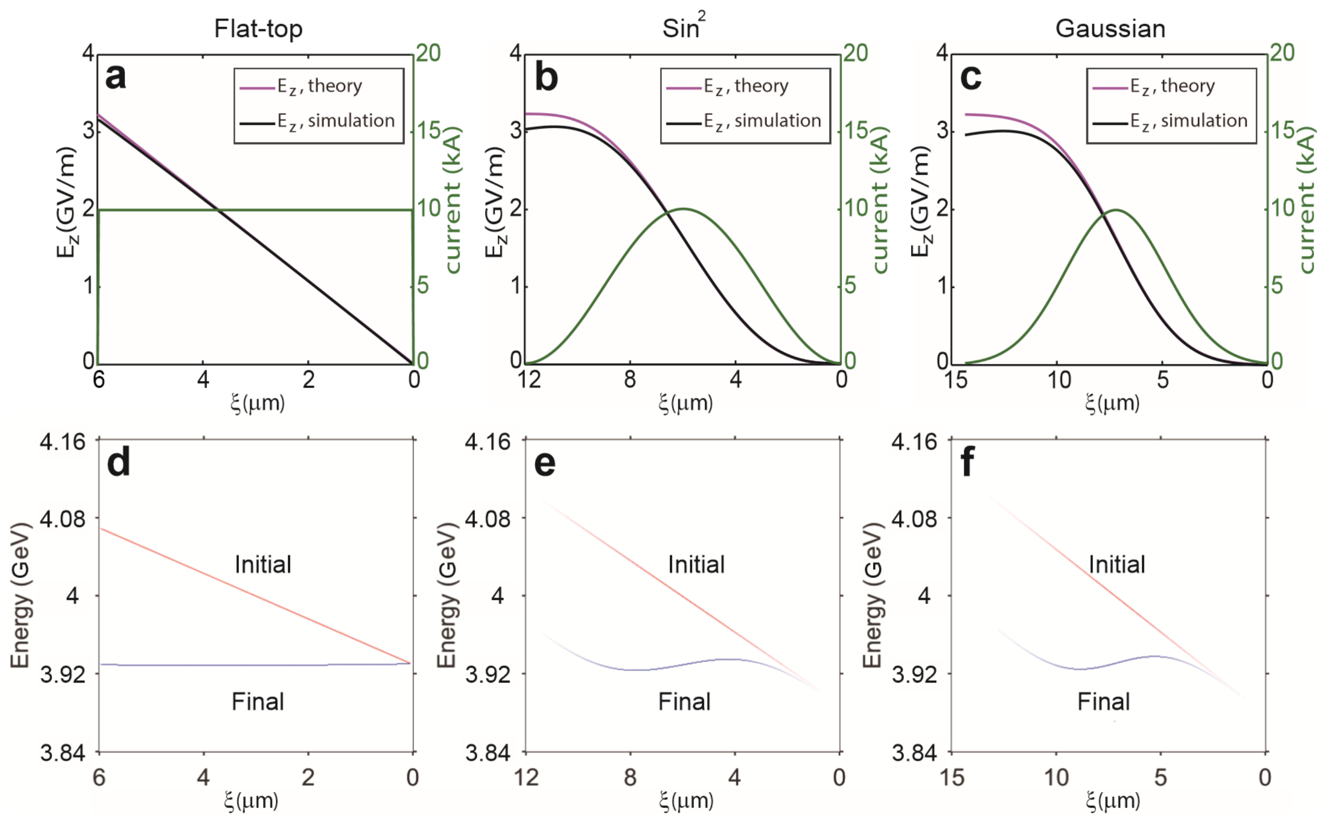
Emittance increase by a factor of 14 (e^-)/ 83(e^+)

Dechirping effects for different current profiles in hollow channel plasma

Initial energy spread 1%

- <0.01% (Flat-top)
- 0.14% (sin^2)
- 0.22% (Gaussian)

A flat-top beam current profile has the best effect for linear energy chirp reduction



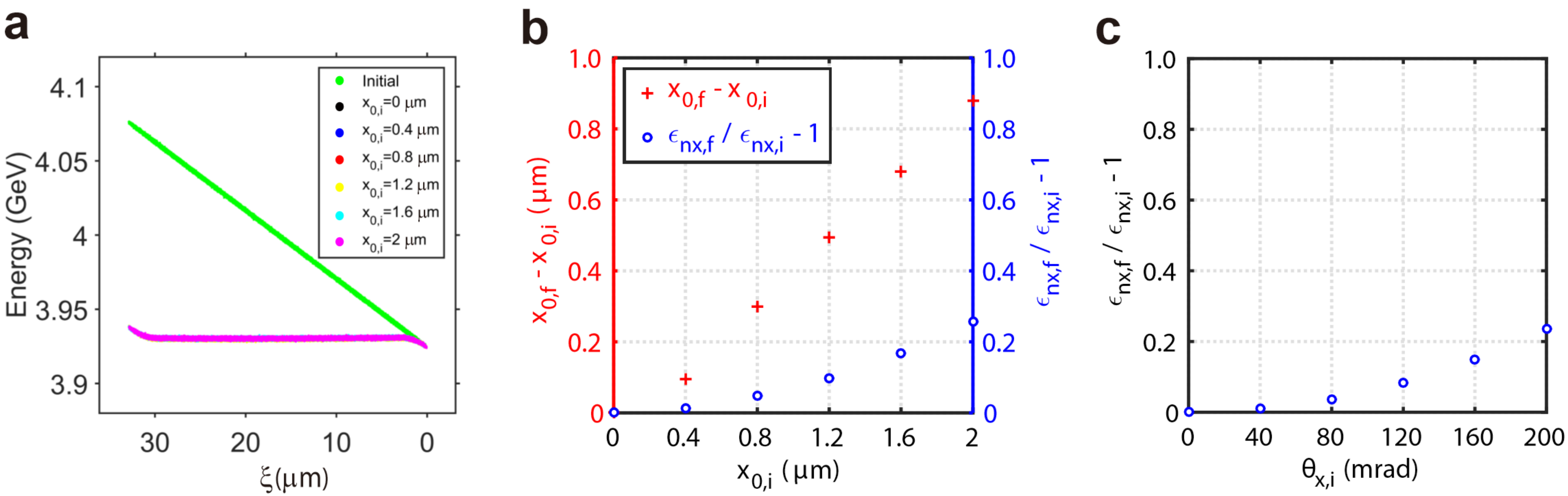
Robustness of a hollow channel plasma dechriper

Off-axis injection

↓

A transverse bending field depending on longitudinal position → Steer the beam towards one side

Projected emittance growth



2μm offset: Negligible beam offset growth; Emittance growth <25%

~200mrad tilt: Emittance growth <25%

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Ultra-compact turn-key lasers for application

4 year+ joint effort of Tsinghua, NCU and Qifeng New Light Source Corp.

The Goal: Building turn-key lasers for real application

a laser built by the user and for the user

Single box 1-50TW laser systems:

✓ very compact

Innovation on high contrast regen amplifier

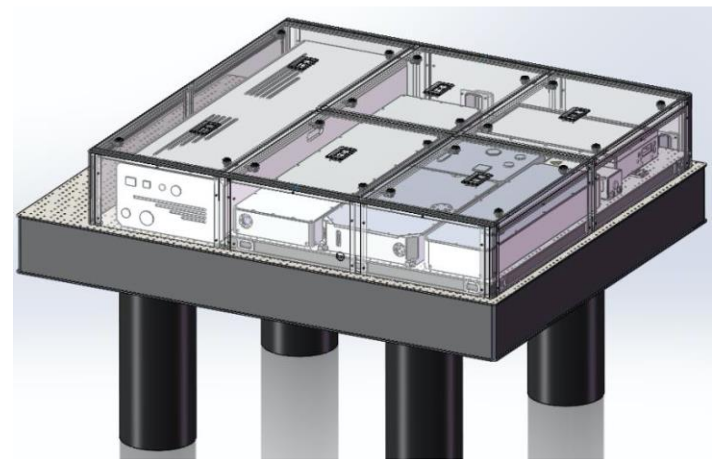
1.4m*0.8m*0.25m for 1-5TW

1.4m*1.5m*0.25m for 20-50TW

✓ turn-key performance for long term operation

Fully sealed subsystems

Independently controlled temperature

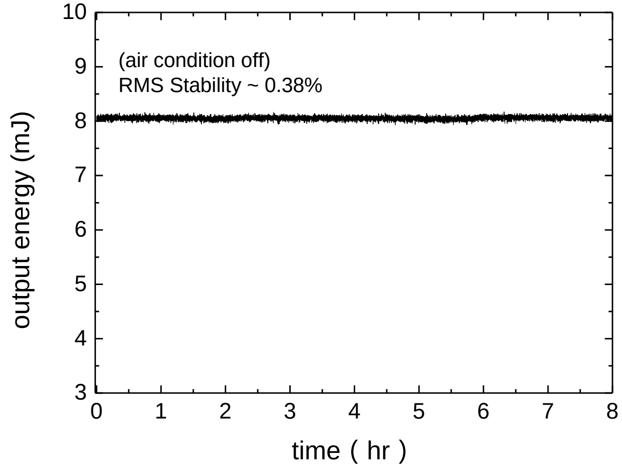


Single Box 20-50TW system

More information please contact Prof. Wei Lu(weilu@tsinghua.edu.cn)

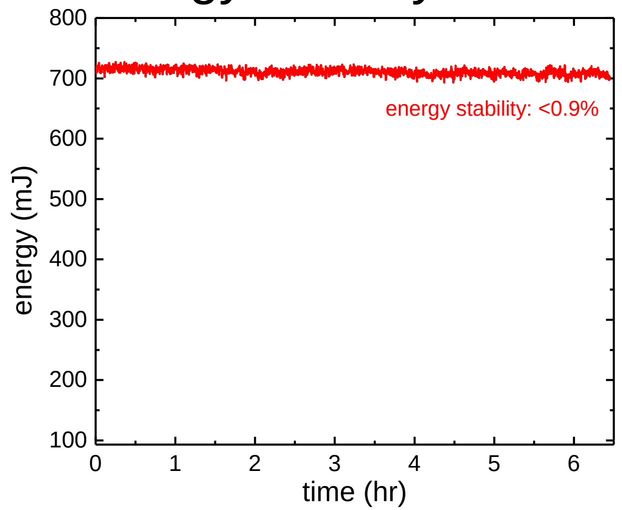
Turn-key performance

- Super stable diode pumped frontend (even for air conditioning is off)



20-50TW Ti:Sapphire laser (0.6~1.5J 10Hz)	
Energy stability（RMS）	<1%
Contrast	$>10^9$(ns)
	$>2x10^{10}$(100ps)
Duration	<30fs
Power	20-50TW

- <1% energy stability for final amplifier



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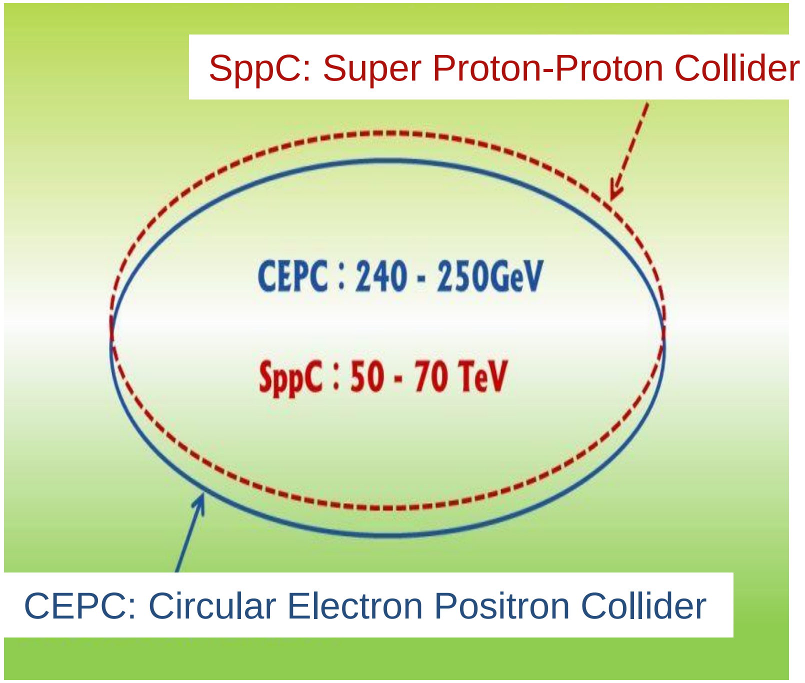
A possible middle step for AAC towards colliders

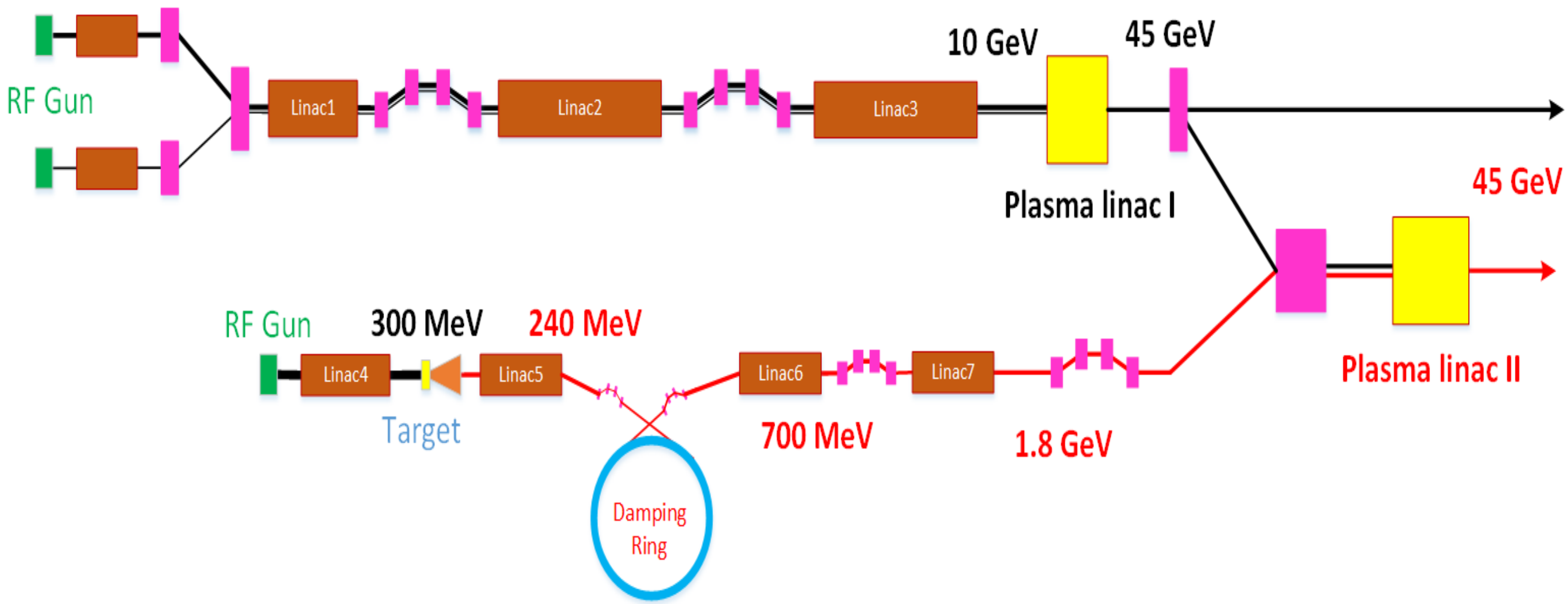
Plasma based injector for 100km CEPC

- CEPC (**Circular Electron Positron Collider**) is a major high energy physics plan under strong promotion in China to build a 100km circular machine for a Higgs Factory.
- A high energy injector (40GeV level) is needed to inject e+/e- beams into the main ring.
- Plasma based schemes (PWFA) may provide a novel and cost effective solution for this injector.
- A joint research group of Tsinghua Univ. and IHEP has been formed since 2017 to study the feasibility of using plasma based acceleration as a novel solution for CEPC injector.

Circular Higgs Factory (Phase I) +SppC (Phase II) at same tunnel



A preliminary design of CEPC plasma based high energy injector



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

Ref: CEPC CDR

Summary

- The external injection from a Linac to a LWFA with ~100% capture efficiency has been experimentally demonstrated.

- For uniform plasma dechirper, the experimental results, combined with high-fidelity 3D PIC simulations indicate a near tenfold reduction of the beam energy spread from 1.28% to 0.13%.

- Next generation ultra-compact turnkey laser systems for application is ready to go. Stay tuned!

- The feasibility of using plasma wakefield accelerator as a high energy injector for CEPC is under intense study, a joint effort of Tsinghua Univ and IHEP.

Thank you for your attention!