Plasma Accelerator Injector Studies at IHEP

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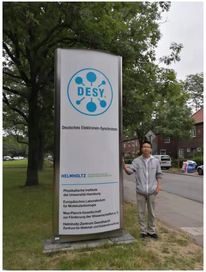
Introduction of Myself

- PhD. at Shanghai Jiao Tong University (06.2015)
- Visiting scholar at University of California, Los Angeles (09.2011 - 08.2012)
- Postdoc at ELI-NP, Romania (12.2015 - 08.2017)
- DESY Fellow at DESY, Germany (09.2017 - 08.2020)
- Associate Researcher at IHEP, China (since 09.2020)



Outline

CEPC Plasma Injector

LWFA Injector for SAPS

Injection Scheme Studies for LWFA/PWFA

Summary

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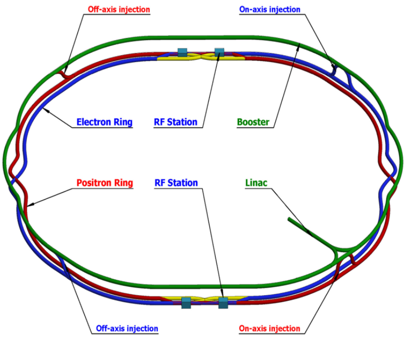
Circular Electron-Position Collider (CEPC)

- 100 km ring
- $E_{\rm cm} \approx 240$ GeV
- Precision measurement of the Higgs boson (and the Z boson)



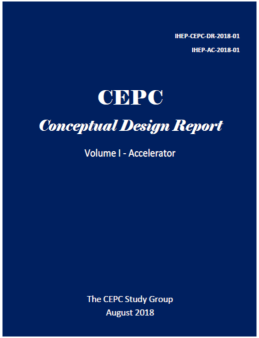


Figure 1: CDR (Acc.) International Review at 2018.6.28-6.30, Final Released at 2018.9.2

CEPC Plasma Injector

- A backup solution for boosting 2.4 / 10 GeV e^+/e^- to 45.5 GeV and injecting to ring
- Base line design:
  - 10 GeV e^- driven PWFA -> witness e^- 10 GeV to 45.5 GeV (transformer ratio $>$ 3.55)
  - 45.5 GeV e^- driven PWFA -> witness e^+ 2.4 GeV to 45.5 GeV (positron acceleration)

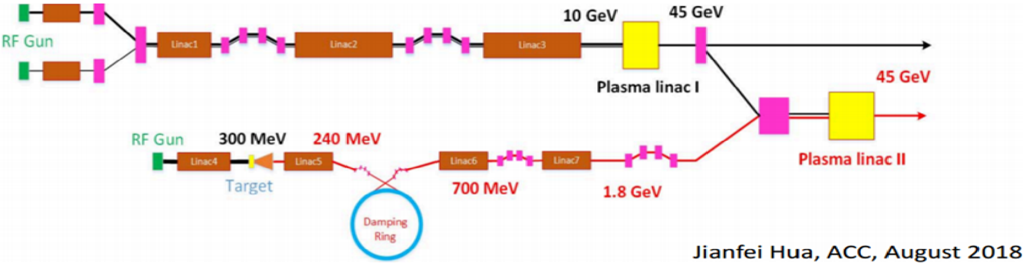


Figure 2: CEPC plasma injector V1.0

CEPC Plasma Injector

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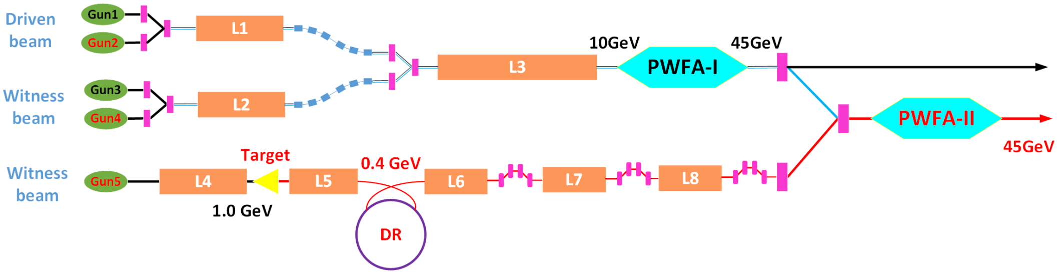

Figure 3: CEPC plasma injector V2.0 [Dazhang Li, CPS, Sept. 2019]

High Transformer Ratio PWFA

- A high transformer ratio (TR) requires a triangular shaped driver
- We have carefully shaped the driver and witness beam for TR > 3.55 and minimize $\Delta E/E$ by beam loading (M. Tzoufras, et al., PRL (2008))

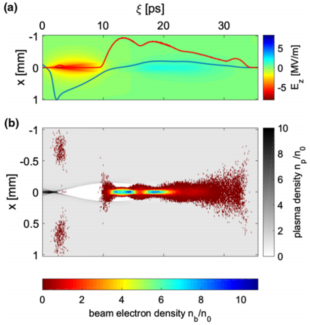

Figure 4: G. Loisch et al., Phys. Rev. Lett. **121**, 064801 (2018).

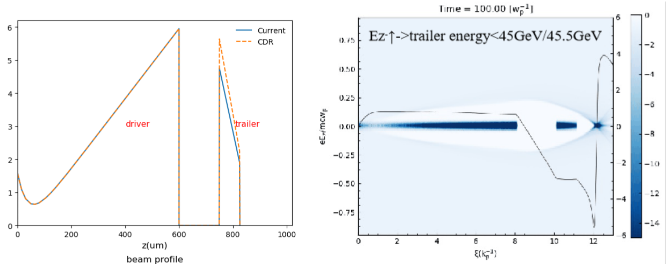

Figure 5: PWFA simulation by X.N. Wang, W.M. An et al. [see X.N. Wang's talk]

Fore-stage Linac Design

- L-band photocathode RF gun
- Challenges
  - High bunch charge, short bunch length (wakefield effect)
  - Longitudinal shape modulation and compressor
  - Small beam size at both transverse plane
- Optimization ongoing

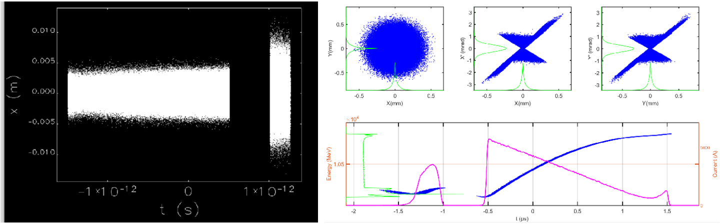

Figure 6: RF gun and Linac design for the preferred current profile [credit: Cai Meng]

Positron Acceleration in Hollow Channel

- Hollow channel PWFA provides acceleration and focusing phase for e^+
- An initial asymmetric driver provides extra tolerance to aiming error
- Beam-loading of e^+ reduces energy spread

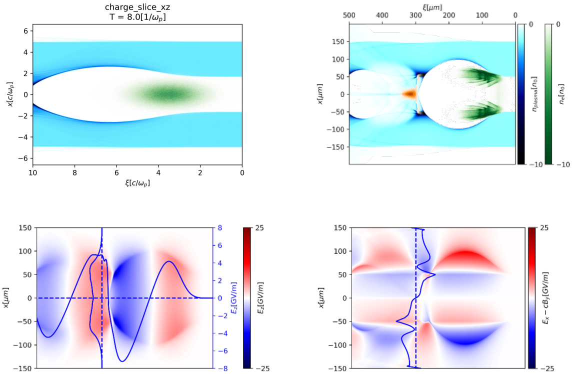

Figure 7: Positron accleration simulation by S.Y. Zhou et al. (submitted) [see S.Y. Zhou's talk]

Generation of Hollow Channel

- Hollow channel: gas ionized by high-order Bessel laser beam
- High-order Bessel laser beam: by Kinoform plate
- Experiments performed at THU

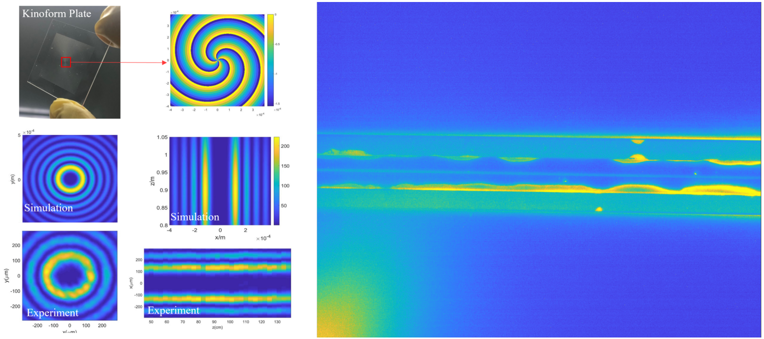

Figure 8: High-order Bessel modes and hollow channel [See Shuang Liu's talk]

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Southern Advanced Photon Source (SAPS)

- A 4th generation photon source to be built in Dongguan city, Guangdong province (South of China)

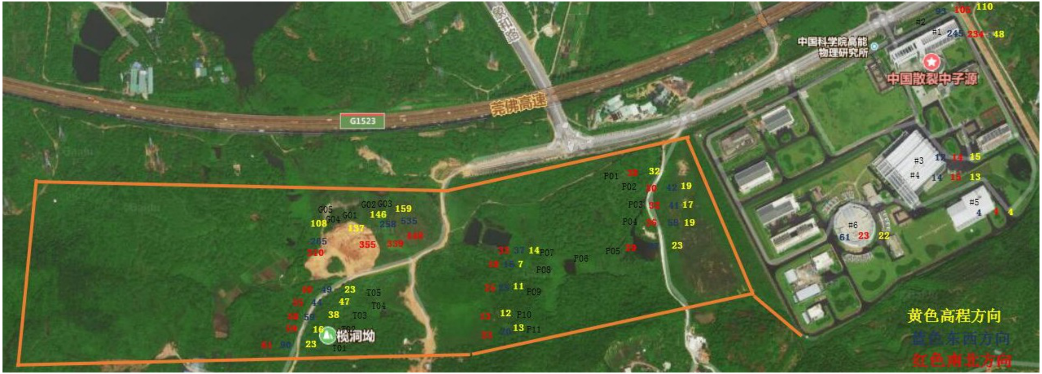

Figure 9: Location of SAPS, near China Spallation Neutron Source (CSNS)

Pre-study of LWFA Injector for SAPS

- LWFA for replacing the electron gun and low-energy Linac
- Objectives
  - 100 TW laser system
  - Stable >500 MeV e-beam generation
  - Beam charge >100 pC
  - Energy spread <5%
  - Normalized emittance <10 mm·mrad

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Injection Schemes

- Injection scheme is a key factor for output beam quality
- The major available injection schemes

Figure 10: Self-injection [Nature 2004]

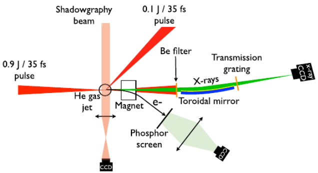

Figure 11: Optical injection [Phys. Rev. Lett. 107, 255003 (2011)]

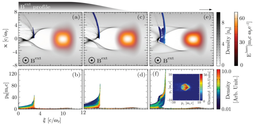

Figure 12: Magnetic injection [Plasma Phys. Control. Fusion 54, 124044 (2012)]

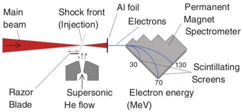

Figure 13: Density transition injection [Phys. Rev. Lett. 110, 185006 (2013)]

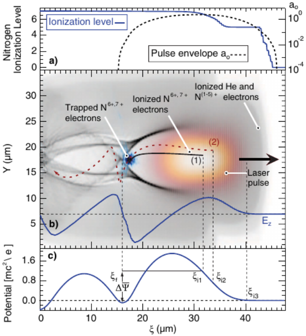

Figure 14: Ionization Injection [Phys. Rev. Lett. 104, 025003 (2010)]

Injection Quality Parameters

- Beam Energy
- Reproducibility
- Beam Charge
- Emittance
- Energy stability
- Energy spread
- ...

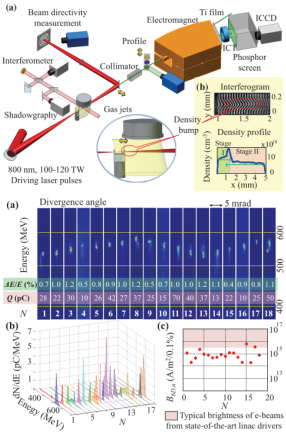

Figure 15: W.T. Wang et al., Phys. Rev. Lett. **117**, 124801 (2016)

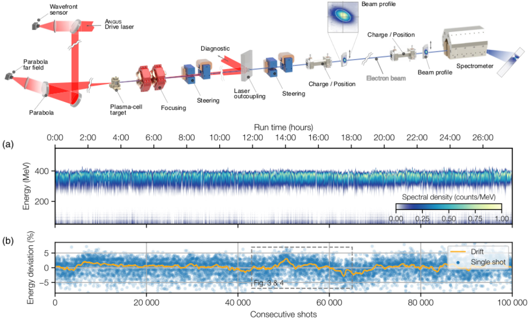

Figure 16: A.R. Maier et al., Phys. Rev. X **10**, 031039 (2020)

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Our Injection Schemes: Self-truncated Ionization Injection

- Ionization Injection is suppressed by the overshot of self-focusing [M. Zeng et al., Phys. Plasmas 21, 030701 (2014)]
- Already demonstrated by a few independent groups
- $\sim 5\%$ energy spread beam can be produced with relatively simple setup

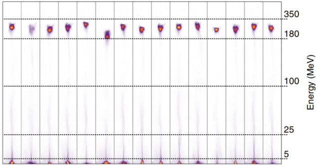

Figure 17: J.P. Couperus et al., Nat. Comm. 8: 487 (2017)

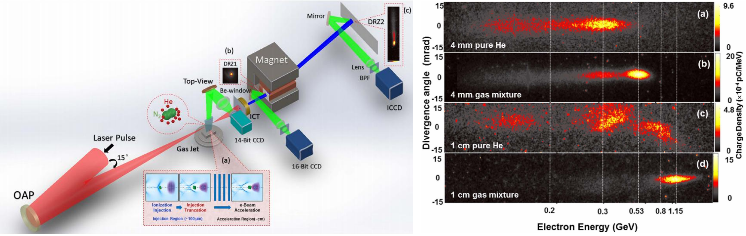

Figure 18: M. Mirzaie et al., Sci. Rep. 5:14659 (2015)

Our Injection Schemes: Dual-color Laser Ionization Injection

- Ionization E-field controlled by the beating of dual-colors due to laser dispersion [M. Zeng et al., Phys. Rev. Lett. 114, 084801 (2015); M. Zeng et al., Phys. Plasmas 23, 063113 (2016)]
- $\sim 1\%$ or lower energy spread may be produced

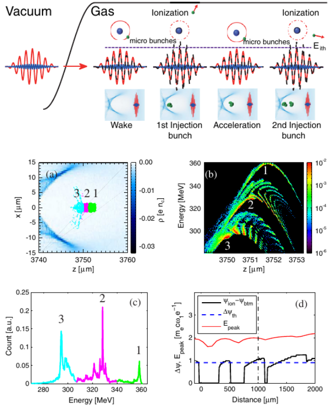

Figure 19: M. Zeng et al., Phys. Rev. Lett. 114, 084801 (2015)

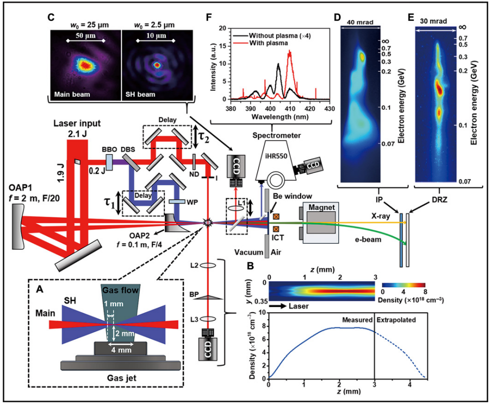

Figure 20: S. Li et al., Sci. Adv. 5, no. 11, eaav7940 (2019)

Our Injection Schemes: Ponderomotively Assisted Ionization Injection

- A sub-relativistic wakefield cannot trap electrons initialized at rest
- A transverse laser pre-accelerates electrons ponderomotively; some electrons can be trapped with critical trapping conditions
- $< 1\%$ slice energy spread beam can be produced

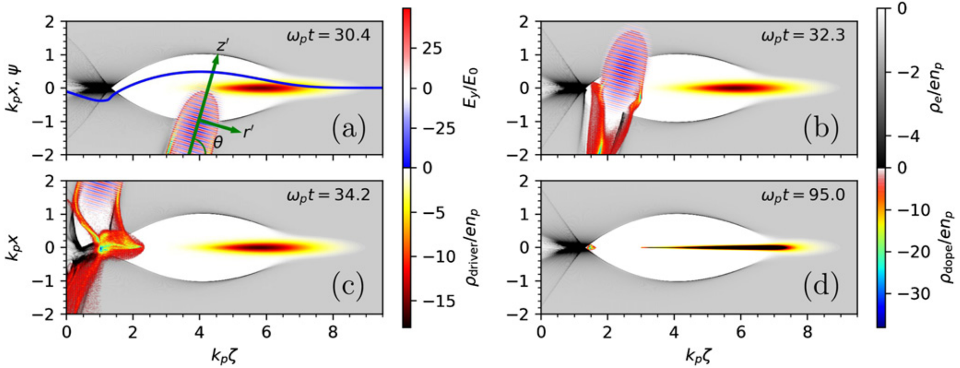

Figure 21: M. Zeng et al., New J. Phys. 22, 123003 (2020)

Outline

Summary

- CEPC plasma injector: 10 GeV e^- beams / 2.4 GeV e^+ beam boosted to 45.5 GeV by PWFA
  - High transformer ratio PWFA
  - Position acceleration in PWFA
- SAPS plasma injector: 500 MeV e-beam by LWFA
  - Good beam quality (energy spread and energy stability) for next RF accelerator stage
- Realization (or reproduce) electron injection schemes at IHEP (preparation for SAPS plasma injector)
  - Self-truncated ionization injection (baseline scheme)
  - Dual-color ionization injection
  - Ponderomotively assisted ionization injection

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