中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

PWFA development at IHEP & CEPC plasma injector

Dr. Dazhang Li
Institute of High Energy Physics
On behalf of on IHEP-THU-BNU Team

Outlines

- **About PWFA and CPI**
- **PWFA challenges and CPI current studies**
- **CPI Roadmap and proposed TF**

Plasma Based Acceleration (PBA): > 1000 $E_{acc.}$

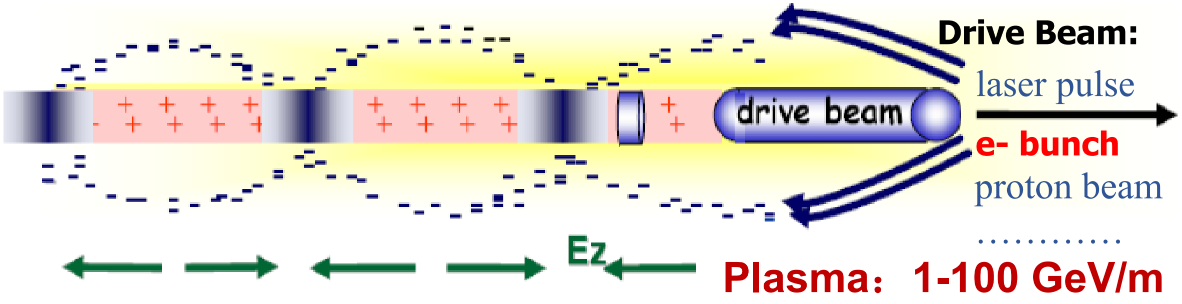
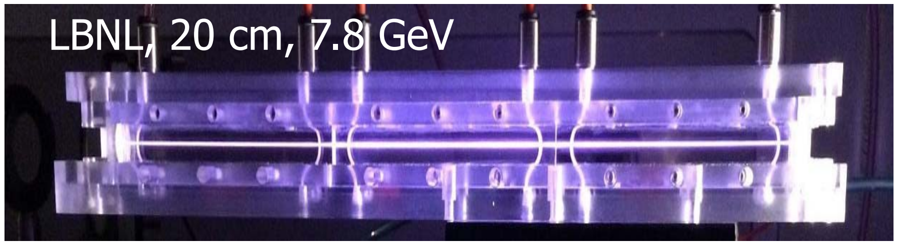
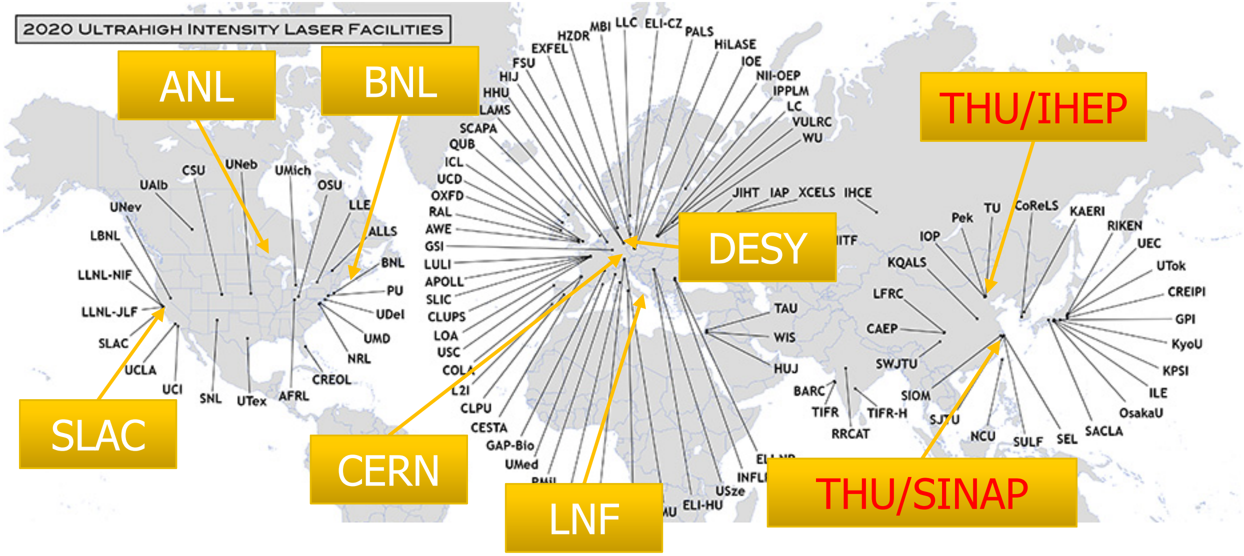


Table-top X/γ sources

High Energy colliders

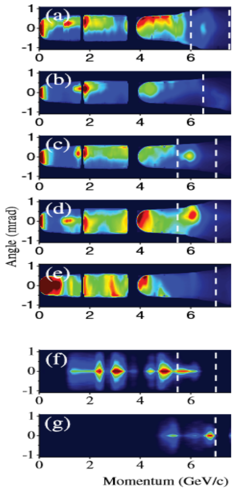
HEDP platforms

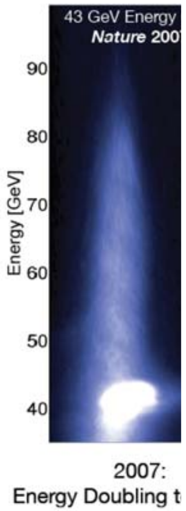


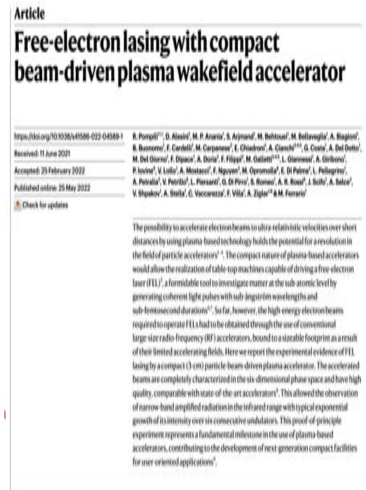


Affiliations/institutes on PWFA Study

Worldwide attentions & great progress in the last 20 years

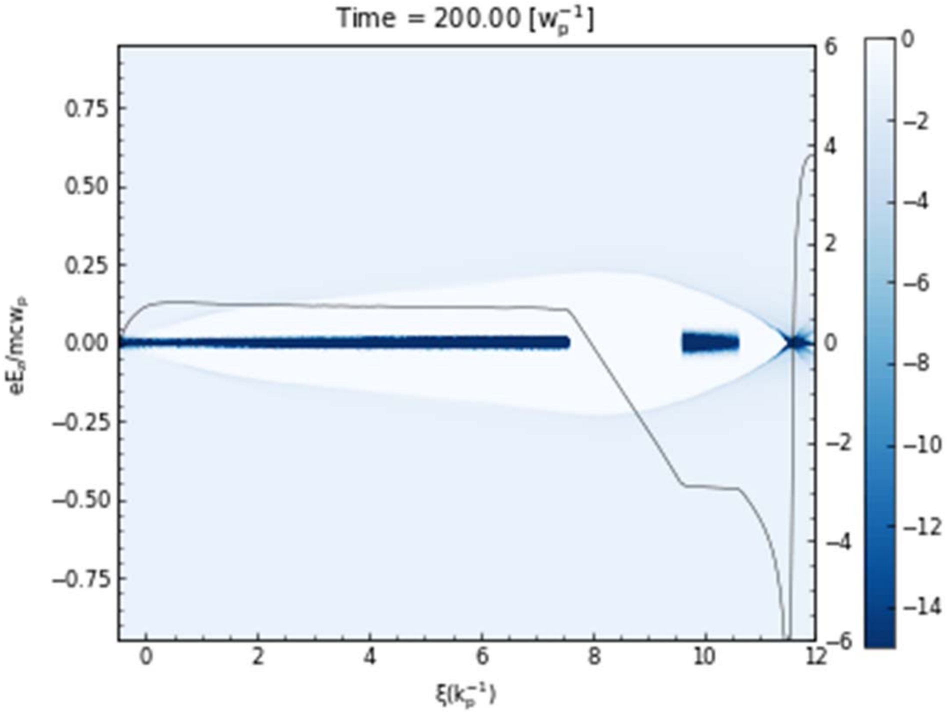


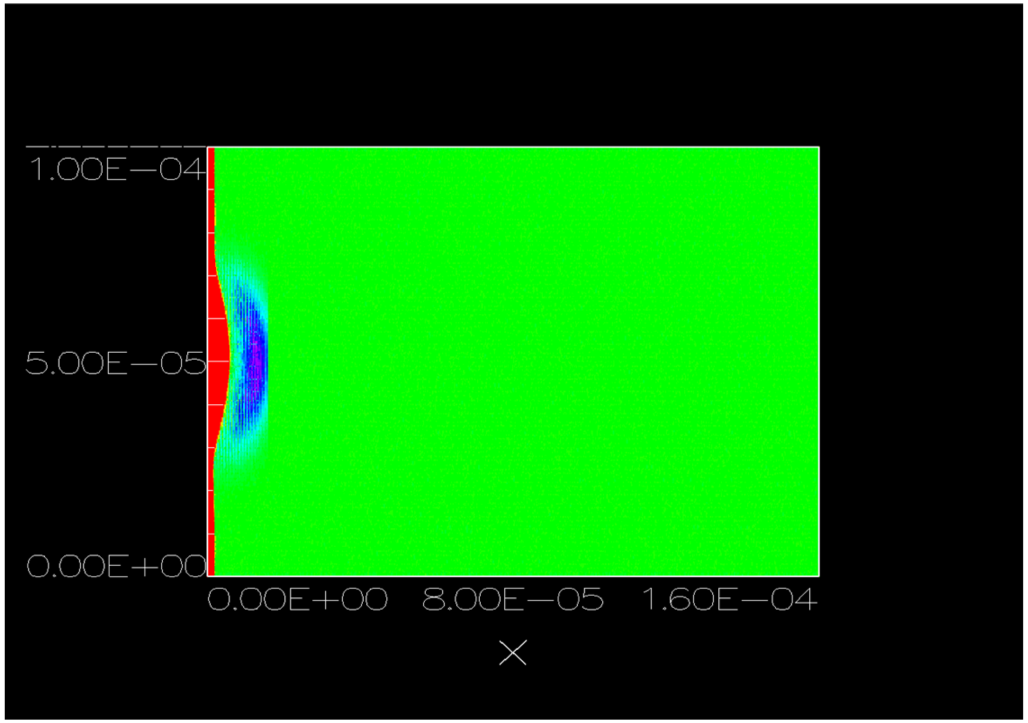



Article

Free-electron lasing with compact beam-driven plasma wakefield accelerator

Plasma/Laser wakefield accelerator (PWFA/LWFA)

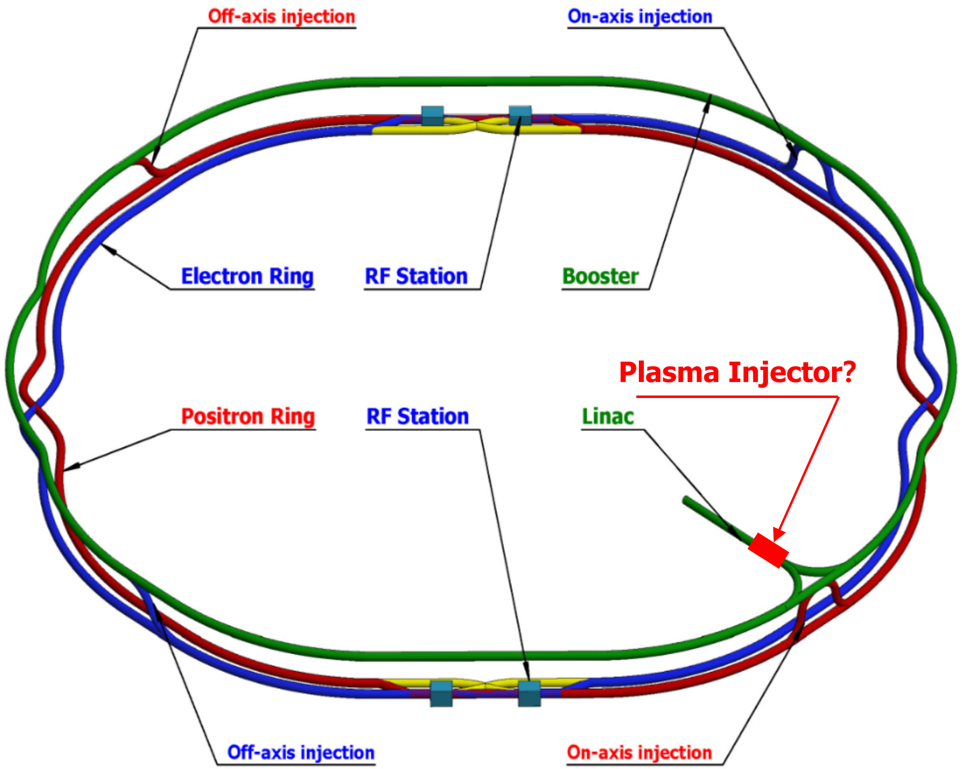




- **Driver: Conventional Accelerator**
  - **Higher average power**
  - **Higher WP to DB efficiency, DB to WB efficiency, Higher repetition rate**

- **Driver: Ultra intense and ultra short laser**
  - **Real tabletop accelerator**
  - **Have potential to increase efficiency and laser's repetition rate ……**

CEPC Plasma Injector (CPI) study since 2017



10 GeV Linac → **100 km Booster** → **Collider Rings**

10 GeV e-/e+ beam in a 100 km ring

- Minimum magnetic field = 28 Gs
- Field error < 28 Gs*0.1% = 0.028 Gs
- Field reproducibility < 29 Gs*0.05% = 0.014 Gs
- The Earth field ~ 0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

10 GeV linac + CT coil magnet, or 30 GeV linac + iron-core magnet ? Both lead to significant cost rise ~ 1 B RMB

CEPC Plasma Injector (CPI) study since 2017

Proposed by Prof. Gao and Prof. Lu on 2017.01

First collaborated group meeting on 2017. 03

Till now, IHEP+THU+BNU, 15+ staffs and 20+ PhDs

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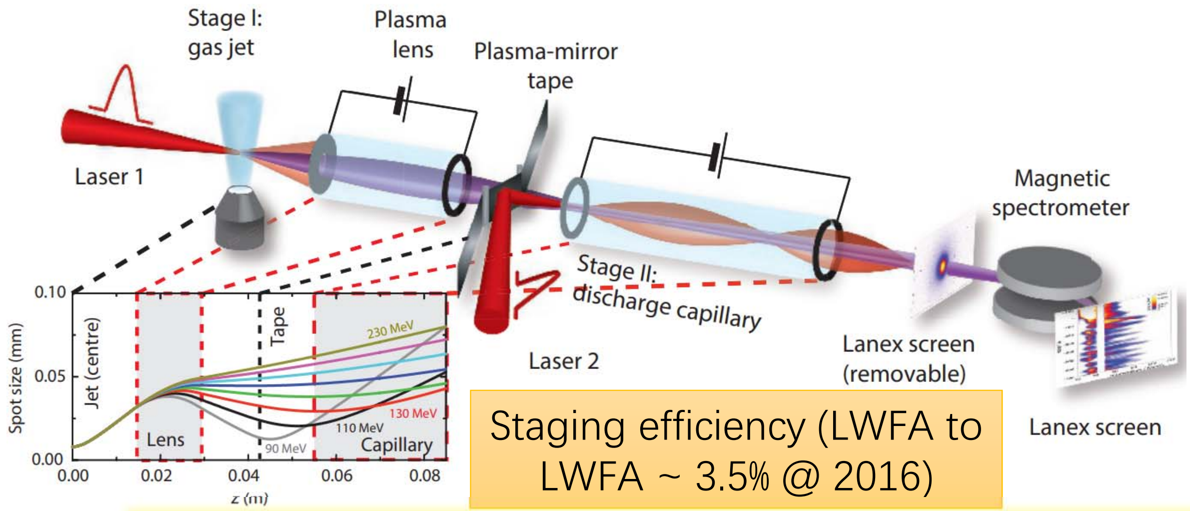
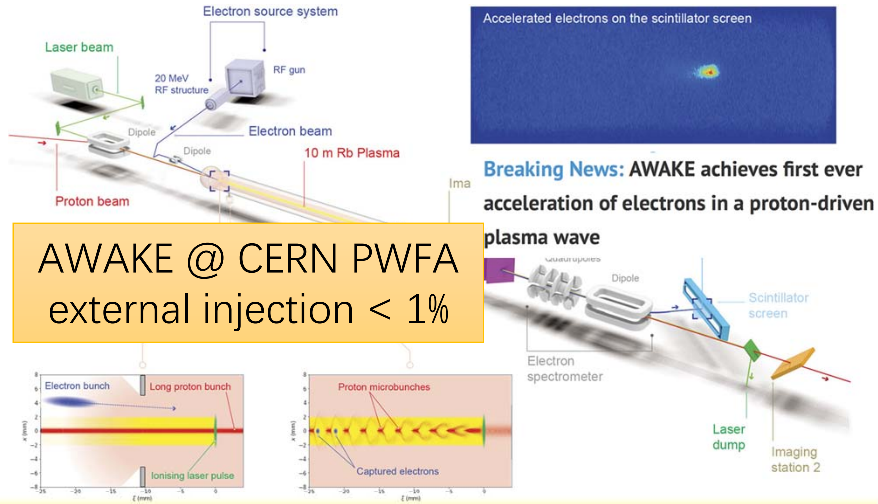
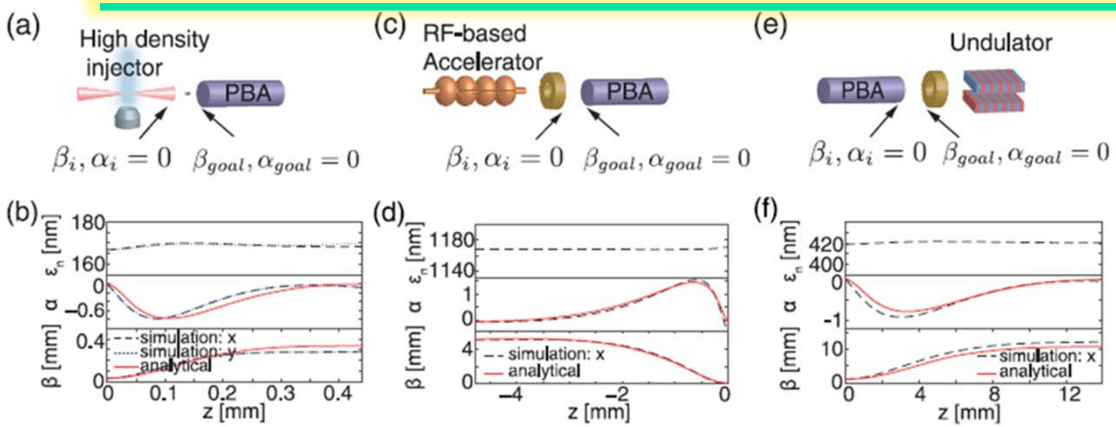
Challenge #1: Staging efficiency



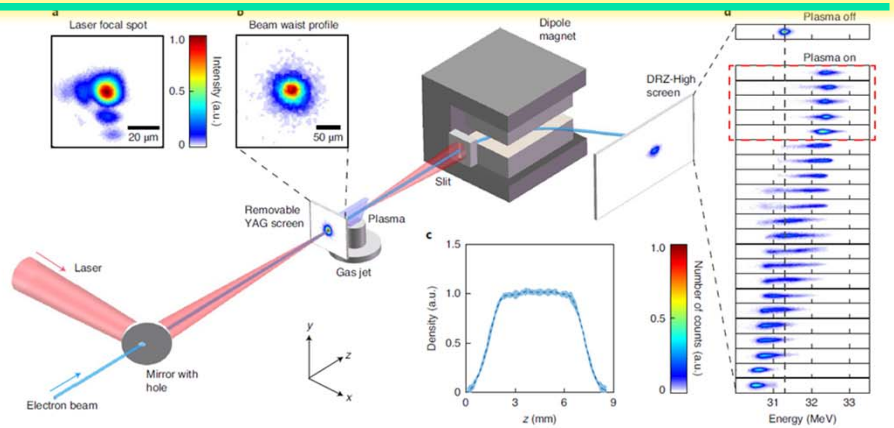
Staging efficiency (LWFA to LWFA ~ 3.5% @ 2016)



AWAKE @ CERN PWFA external injection < 1%



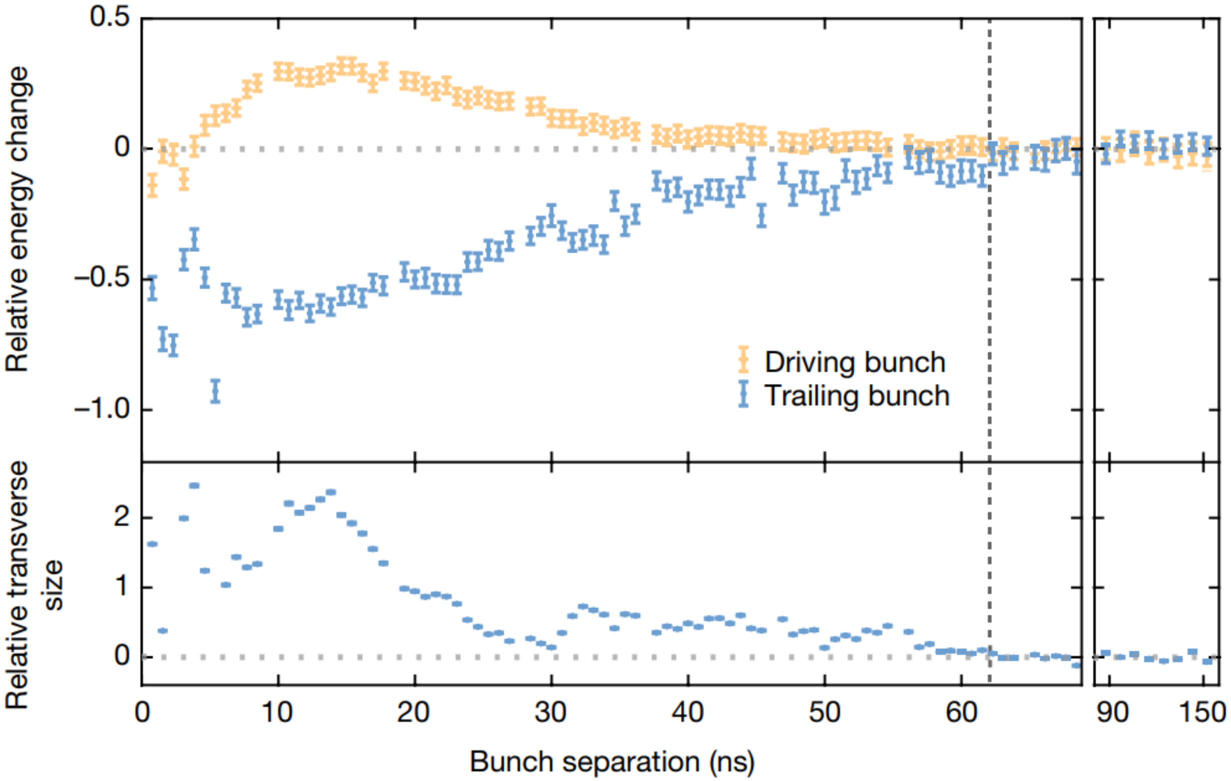
Xu, X. L., et al. (2016). Phys Rev Lett **116(12): 124801.**



Wu, Y. P., et al. (2021). Nature Physics **17(7): 801**

Challenge #2: High repetition rate plasma sources

Plasma recovery time ~ 63 ns → Max Rep. Rate ~ 10 MHz



D'Arcy et al., Nature 603, 58-62 (2022)

	Plasma accelerator	ILC	CLIC
Inter-bunch separation	O(100 ns)	554 ns	0.5 ns
Bunch-train length	???	726 μs	156 ns
Macro-pulse separation	???	100 ms	20 ms
Max. # of bunches per second	**???**	**13120**	**15600**

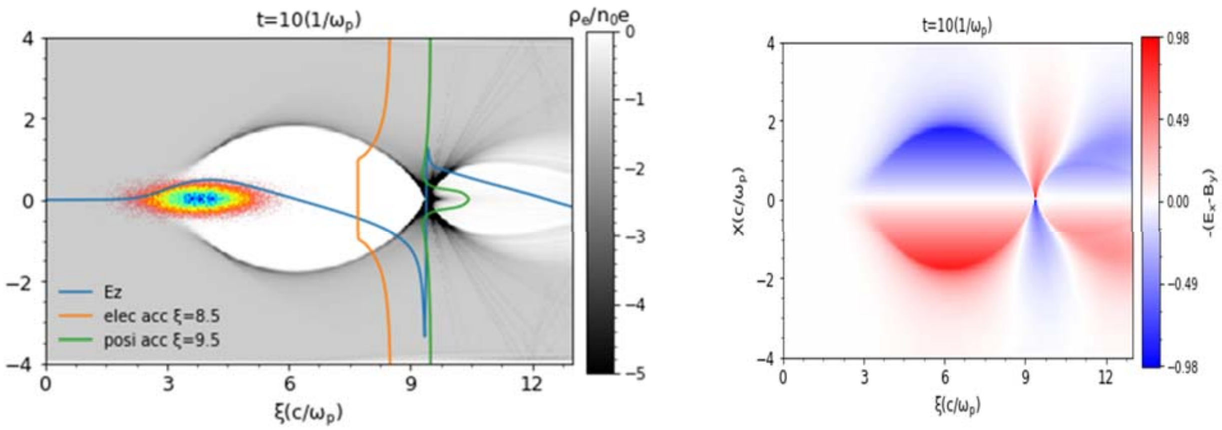
Right now < 10 or even < 1

- Have potential but not be proved
- For LWFA, high power laser's repetition rate also need to be improved

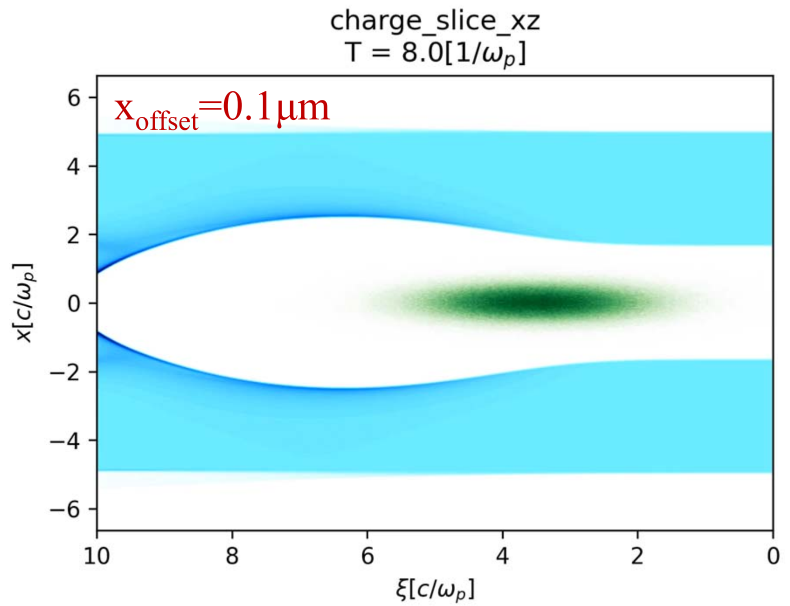
Challenge #3: positron acceleration

A "perfect" wakefield means:

- **Flat longitudinal wakefield, particles at different position experience same Ez**
- **Transverse wakefield can provide focusing forces to the accelerated particles**



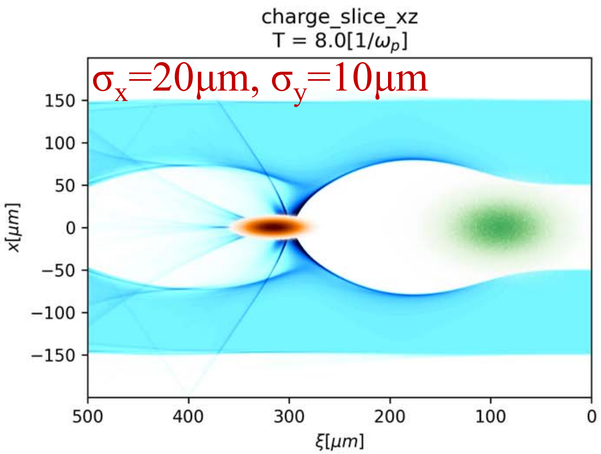
So, the blowout wakefield in uniform plasmas is quite fit for e- acceleration, while unfit for e+ acceleration

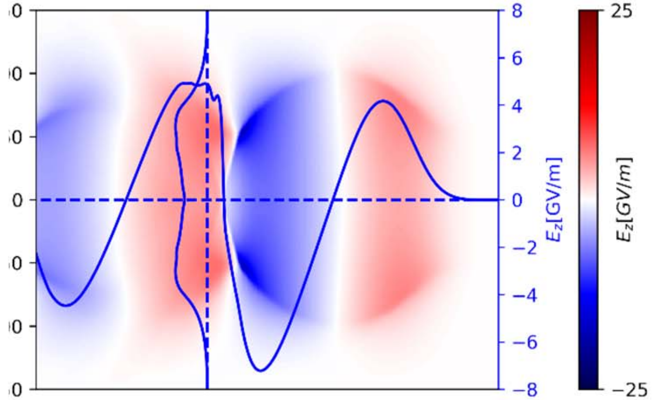


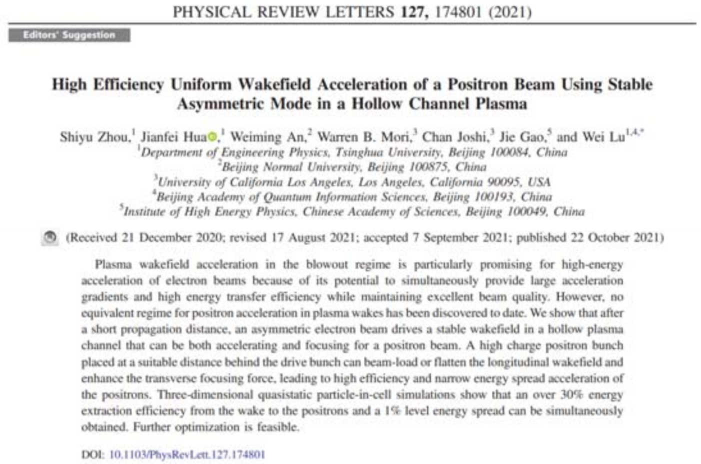
- **High efficiency 60%**
- **Low energy spread ~0.5%**
- **Small emittance growth**
- **Need e- driver, e+ trailer and plasma channel exactly coaxial**

Shiyu Zhou, W. Lu et al., CEPC Conceptual Design Report (2018)

Challenge #3: positron acceleration






PHYSICAL REVIEW LETTERS **127,** 174801 (2021)

Editors' Suggestion

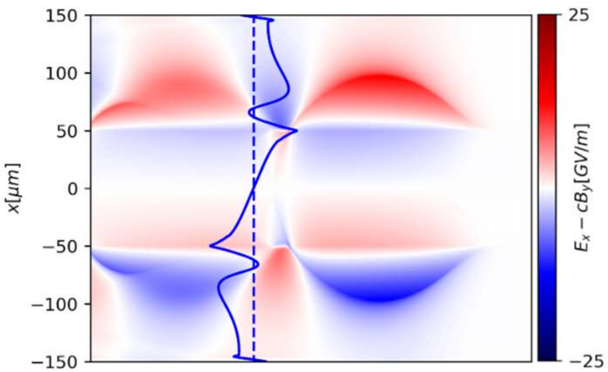
High Efficiency Uniform Wakefield Acceleration of a Positron Beam Using Stable Asymmetric Mode in a Hollow Channel Plasma

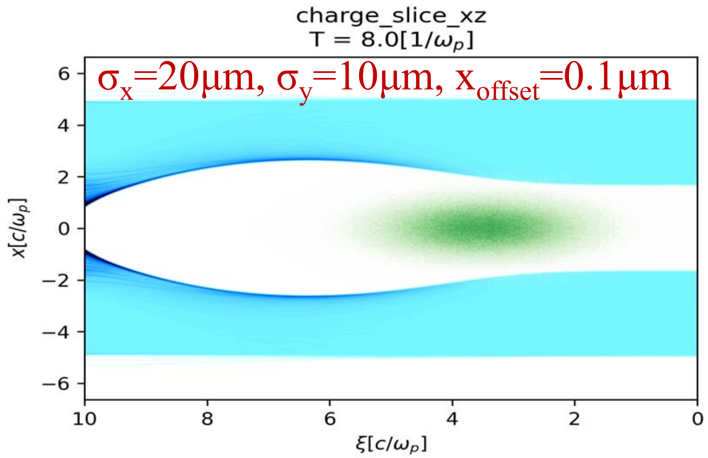
Shiyu Zhou,[1] Jianfei Hua,[1] Weiming An,[2] Warren B. Mori,[3] Chan Joshi,[3] Jie Gao,[5] and Wei Lu[1,4,*]
[1]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[2]*Beijing Normal University, Beijing 100875, China*
[3]*University of California Los Angeles, Los Angeles, California 90095, USA*
[4]*Beijing Academy of Quantum Information Sciences, Beijing 100193, China*
[5]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

(Received 21 December 2020; revised 17 August 2021; accepted 7 September 2021; published 22 October 2021)

Plasma wakefield acceleration in the blowout regime is particularly promising for high-energy acceleration of electron beams because of its potential to simultaneously provide large acceleration gradients and high energy transfer efficiency while maintaining excellent beam quality. However, no equivalent regime for positron acceleration in plasma wakes has been discovered to date. We show that after a short propagation distance, an asymmetric electron beam drives a stable wakefield in a hollow plasma channel that can be both accelerating and focusing for a positron beam. A high charge positron bunch placed at a suitable distance behind the drive bunch can beam-load or flatten the longitudinal wakefield and enhance the transverse focusing force, leading to high efficiency and narrow energy spread acceleration of the positrons. Three-dimensional quasistatic particle-in-cell simulations show that an over 30% energy extraction efficiency from the wake to the positrons and a 1% level energy spread can be simultaneously obtained. Further optimization is feasible.

DOI: 10.1103/PhysRevLett.127.174801





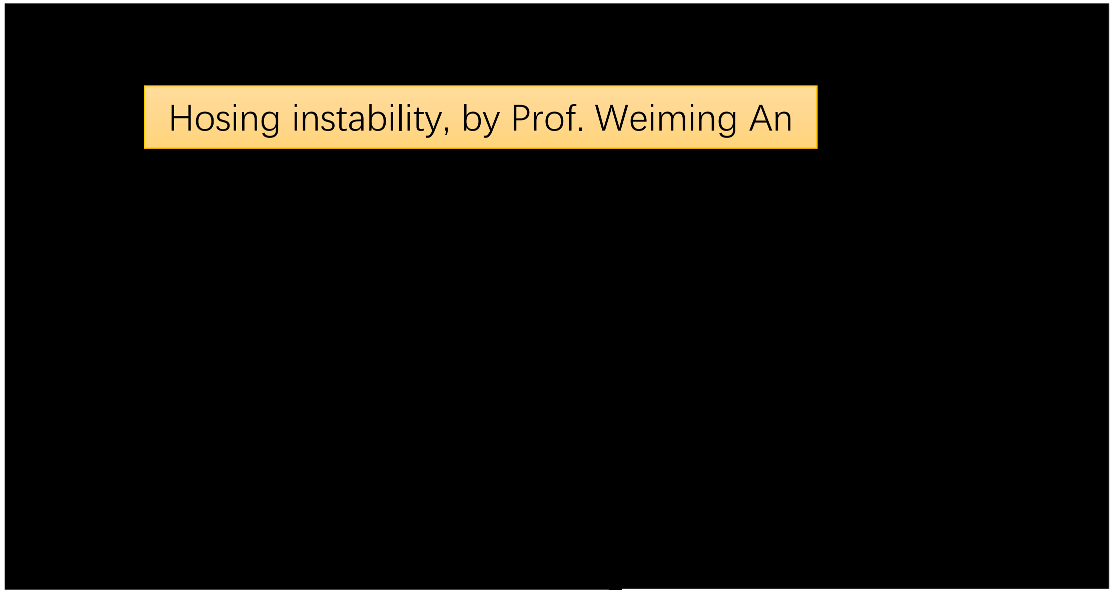
Gradient~5GeV/m,

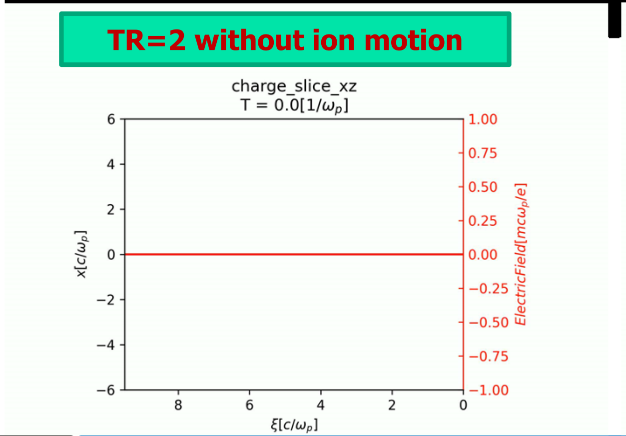
Efficiency >30%,

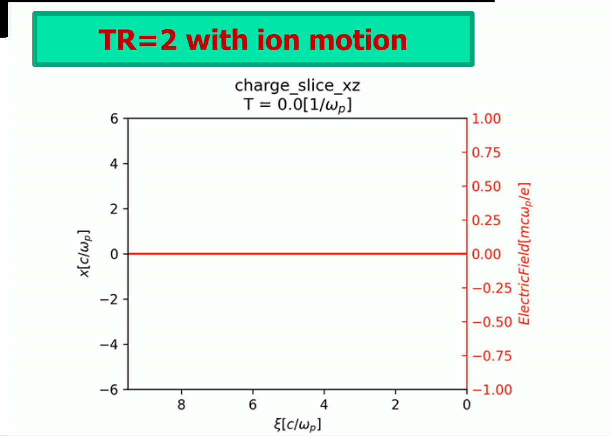
Energy Spread~1.5%

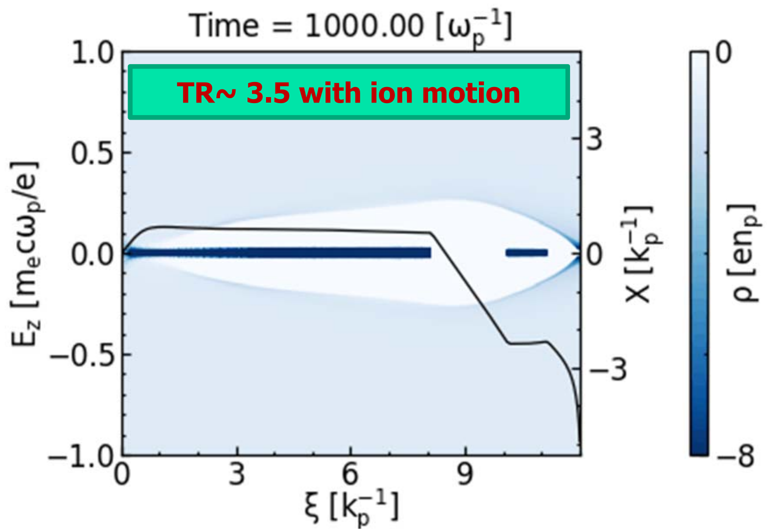
Shiyu Zhou, W. Lu et al., PRL 127 174801 (2020)

Challenge #4: long distance acc. hosing instability



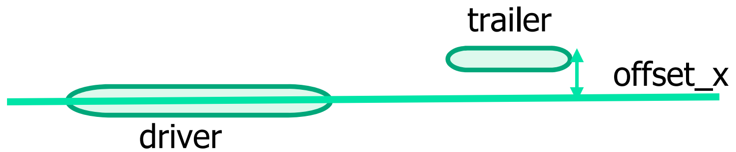




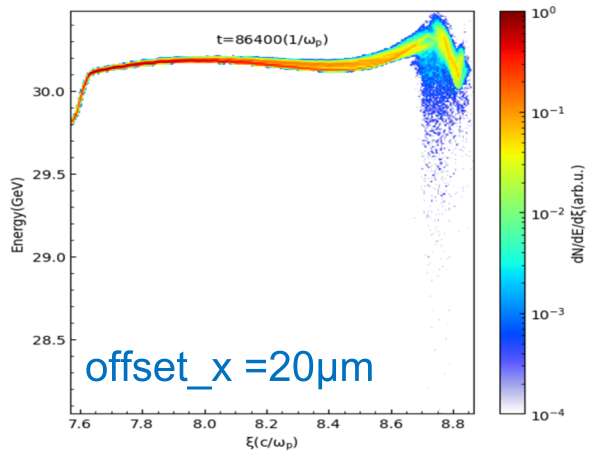


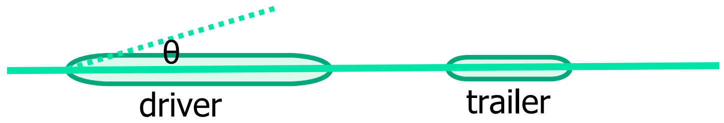
- In simulation, TR ~ 2 is stable enough
- Hosing instability may lead to emittance growth
- BNS damping may mitigate hosing instability, ion motion, for example
- Other damping sources exist in a real PBA, but not included in the simulations

Challenge #4: long distance acc. hosing instability

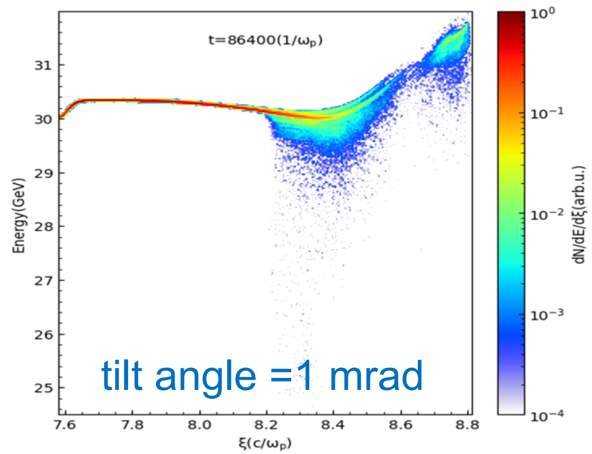


Offset (x direction)	4 μm	12 μm	20 μm	30 μm
Bunch charge [nC]	1.197	1.197	1.174	1.079
Energy [GeV]	30.01	30.04	30.16	30.37
RMS energy spread	0.43	0.41	0.22	0.72





Tilt angle	10 μrad	100 μrad	1 mrad
Bunch charge [nC]	1.197	1.197	0.903
Energy [GeV]	30.01	30.01	30.24
RMS energy spread	0.41	0.41	0.65

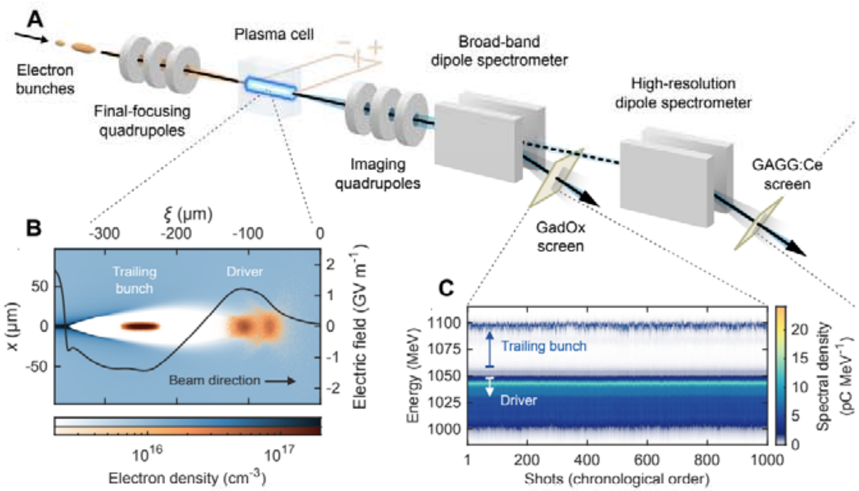


Challenge #4: long distance acc. hosing instability

Encouraging: recent demonstration of emittance preservation

Material provided by Carl A. Lindstrøm, Univ. Oslo

Experiment at FLASHForward



Experimental setup: 1 GeV beam driver with 400 pC charge

50 mm plasma cell: peak density ~ $1.2 \times 10^{16} cm^{-3}$ (with ramps)

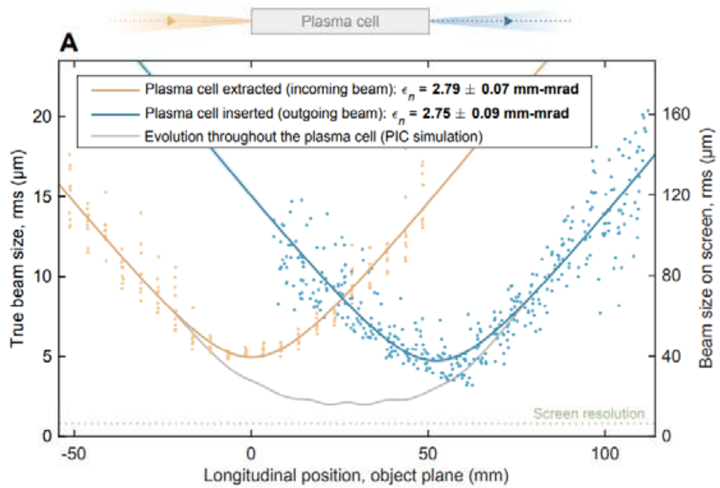
Stable operating point: 40 MeV energy gain, 22% transfer efficiency

(1.4 GV/m estimated peak field)

Preservation of: **Charge** (40 pC), in 41% of shots

Energy spread (0.12% FWHM or lower), in 62% of shots

Emittance in x dfirection



Lindstrøm, Carl Andreas, et al. "Preservation of beam quality in a plasma-wakefield accelerator." (2022).

Real life is tough, but not hopeless

Challenge #5: Efficiency enhancement → LWFA

CPI V2.0 TR≥3.5

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	77
(matched) Spot size(um)	3.89	8.65
Charge (nC)	5.8	0.84
Beam distance (um)	149	

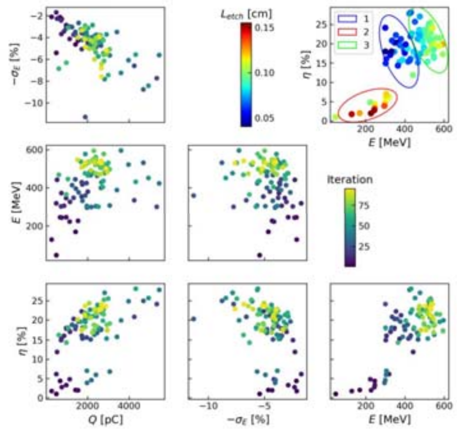
Accelerating distance (m)	10.65
Trailer energy $E(GeV)$	45.5
Normalized emittance $\epsilon_n (mm\ mrad)$	98.44
Charge(nC)	0.84
Energy spread $\delta_E (\%)$	0.56
Efficiency (%) (driver → trailer)	**59.1**

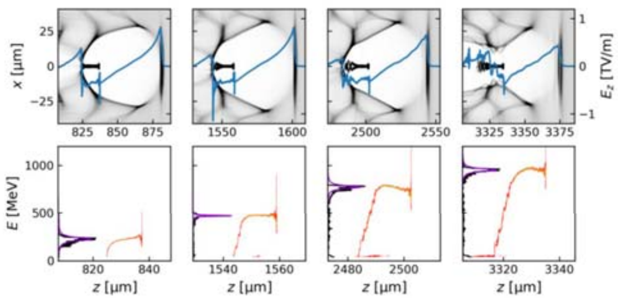
PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 091303 (2023)

High quality beam produced by tightly focused laser driven wakefield accelerators

Jia Wang, Ming Zeng,* Dazhang Li,† Xiaoning Wang, and Jie Gao
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China and University of Chinese Academy of Sciences, Beijing 100049, China

By using ~ 120 TW lasers, electron beams with ~400 MeV, ~1% energy and ~1 nC bunch charge are generated





By introducing Bayesian optimization, the energy transfer efficiency is more than 20%, even to 30%

Challenge #5: Efficiency enhancement → LWFA

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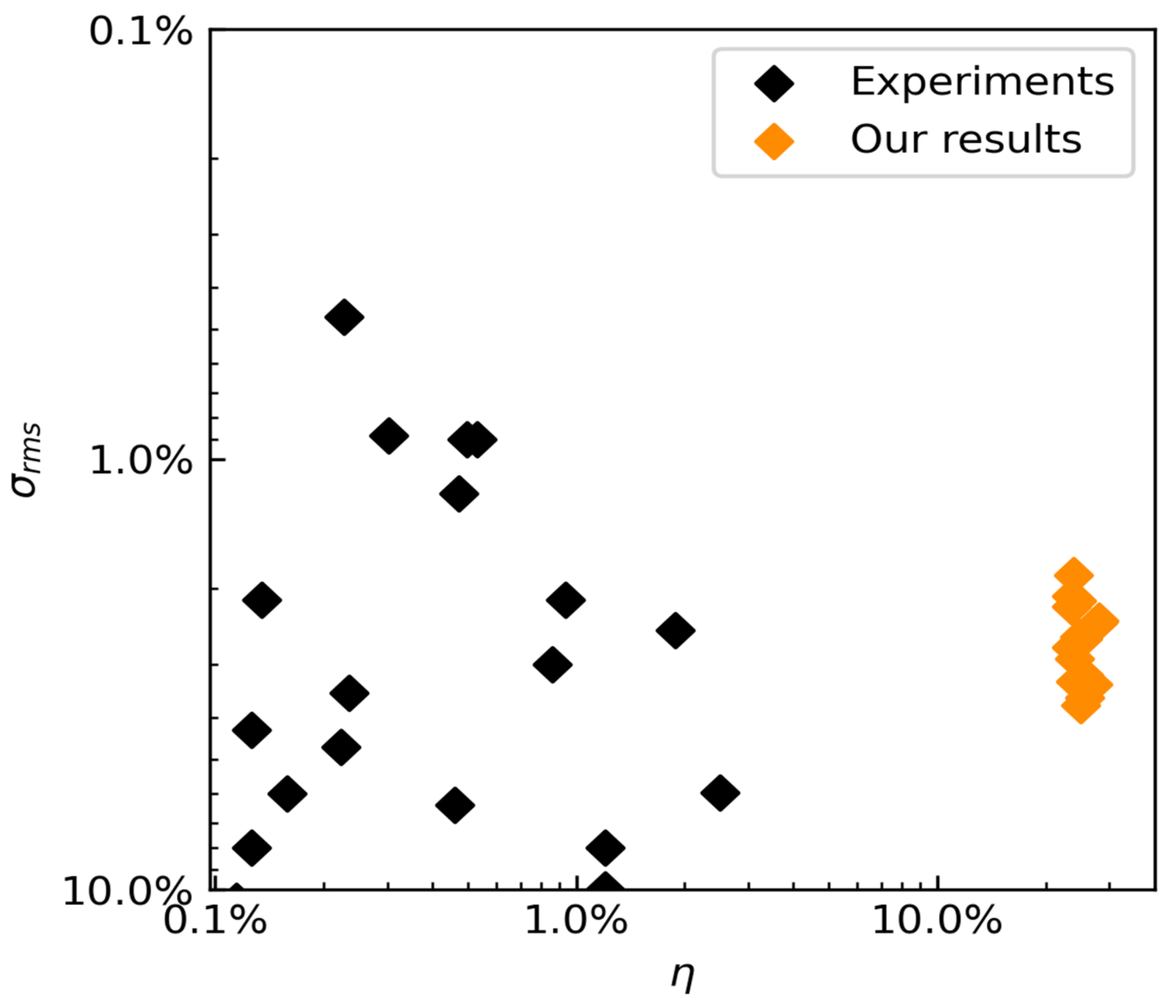

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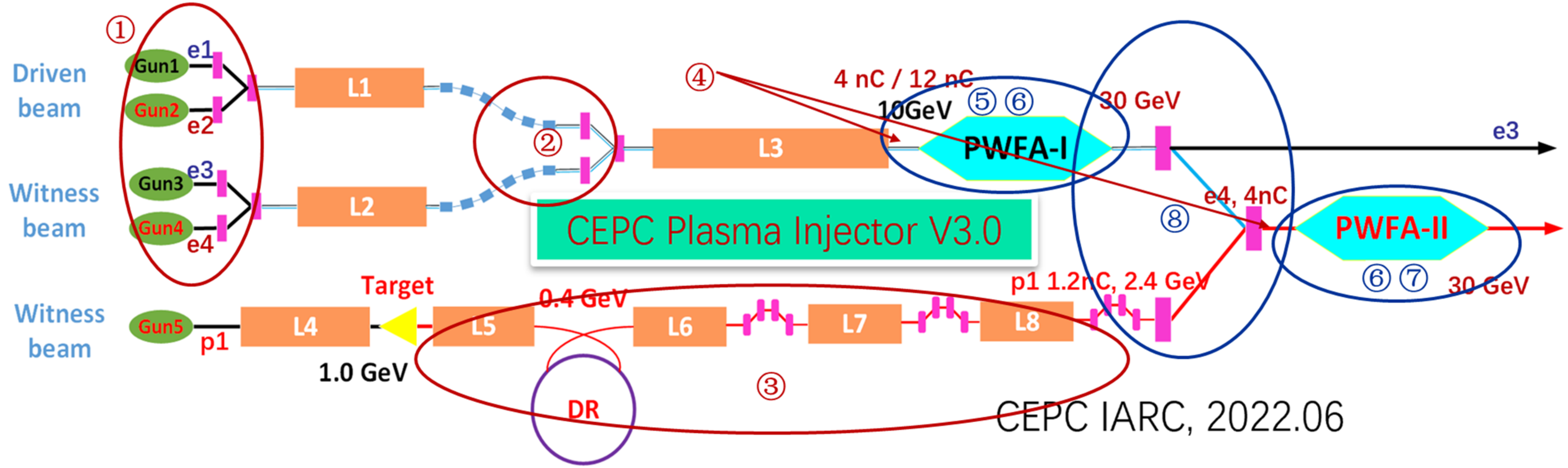
KEY issues for CPI----Lack of experimental studies



Key issues for conventional accelerator:

① High charge longitudinal shaped bunch;

② High current beams combination;

③ Low emittance e+ beamline

④ Final focus system design and optimization

Key issues for plasma wakefield accelerator:

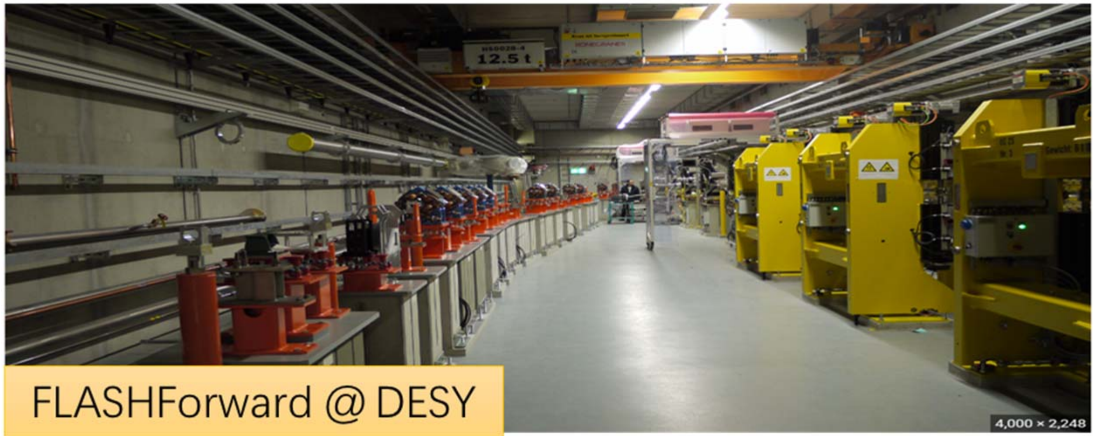
⑤ High TR e- PWFA and hosing instability;

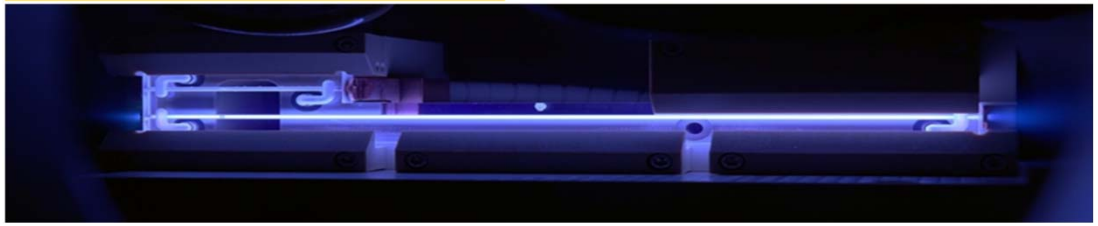
⑥ High repetition rate stable plasma sources

⑦ High quality and high efficiency e+ PWFA

⑧ Staging / Cascaded acceleration

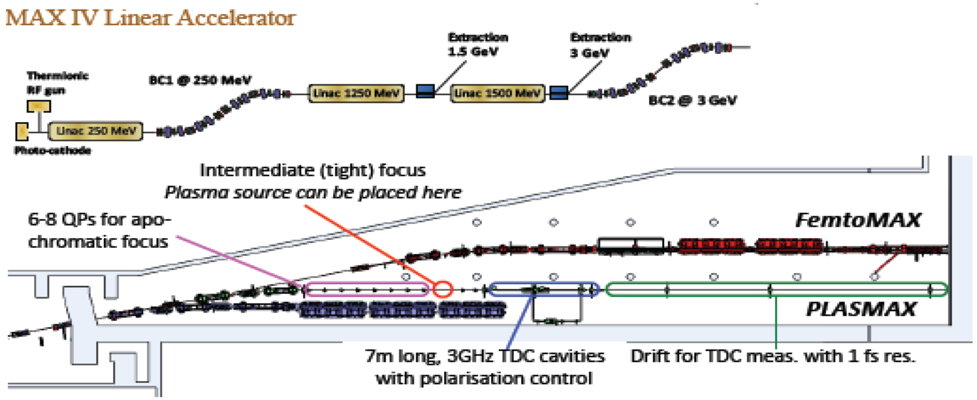
To address all the key issues need (dedicated) TFs





PLASMAX @ MAX IV

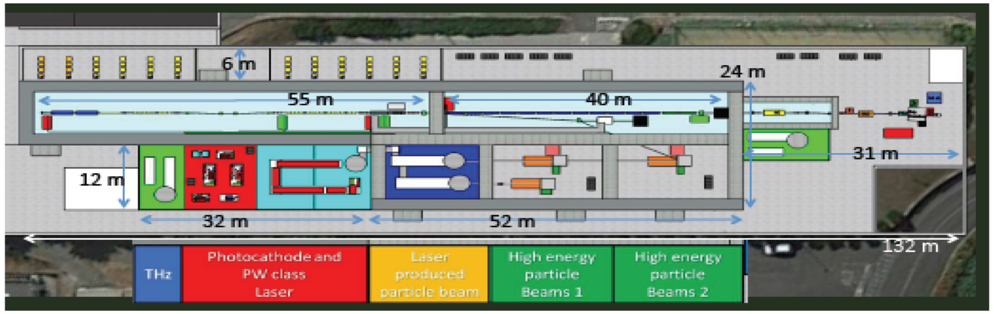
3GeV Electrons, Proposed for 2020+



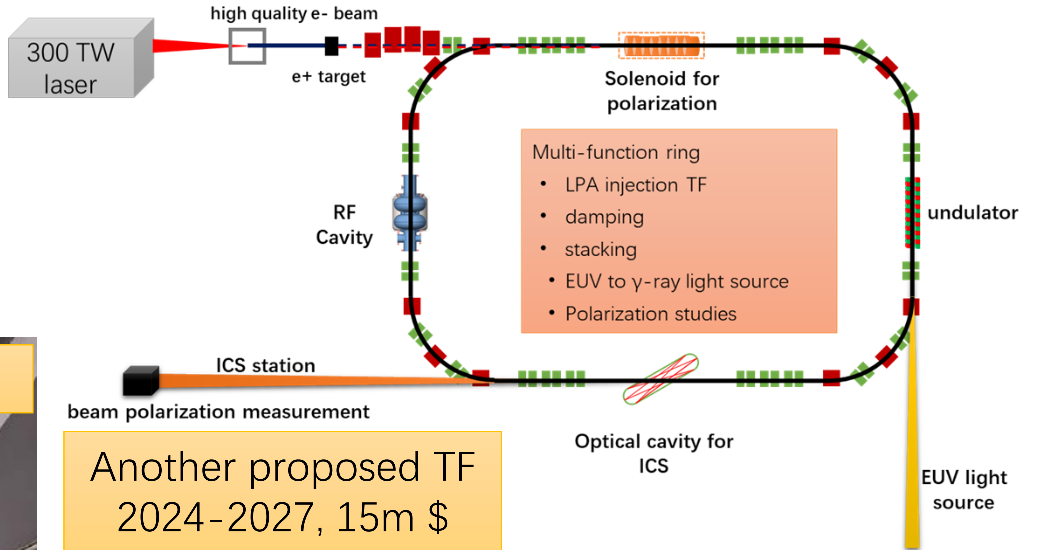
EuPRAXIA @ SPARC_LAB or DESY

1-5GeV Electrons, Proposed

EuPRAXIA SPARC LAB DESY



IHEP proposed PBA TF in the last few years



- Linac + PWFA and LPA + Ring, totally complementary
- PBA acts as an injector to conventional accelerator is a mid-step. In China, it maybe more practical than the EU or USA colleagues' choice: a 10 GeV PBA stage
- The ultimate goals are the same: more efficient, more compact, green PBA colliders in near future


Thank you and welcome to IHEP

Cost and Power consumption: LC Vs. PBA LC

Proposal Name	c.m. energy [TeV]	Luminosity/IP [10^{34} cm^{-2}s^{-1}]	Yrs. pre-project R&D	Yrs. to 1st physics	Constr. cost [2021 B$]	Electr. power [MW]
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3]-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC[3]-0.38	0.38	2.3	0-2	13-18	7-12	110
CCC[3]	0.25	1.3	3-5	13-18	7-12	150
HELEN[3]	0.25	1.4	5-10	13-18	7-12	110
FNAL e^+e^- circ.	0.24	1.2	3-5	13-18	7-12	200
CERC[3]	0.24	78	5-10	19-24	12-30	90
ReLiC[1,3]	0.24	165 (330)	5-10	>25	7-18	315
ERLC[3]	0.24	90	5-10	>25	12-18	250
XCC $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
$\mu\mu$-Higgs	0.13	0.01	>10	19-24	4-7	200
ILC-3 **59 km**	3	6.1	5-10	19-24	18-30	~400
CLIC-3 **50 km**	3	5.9	3-5	19-24	18-30	~550
CCC-3	3	6.0	3-5	19-24	12-18	~700
ReLiC-3	3	47(94)	5-10	>25	30-50	~780
$\mu\mu$Collider[1]-3	3	2.3(4.6)	>10	19-24	7-12	~230
LWFA-LC-3 **1.3 km**	3	10	>10	>25	12-80	~340
PWFA-LC-3 **14 km**	3	10	>10	19-24	12-30	~230
SWFA-LC-3	3	10	5-10	>25	12-30	~170

- Size:
  - LWFA LC << PWFA LC << LC
  - But NOT 1000 times smaller due to beam deliver section
- Power consumption
  - PBA LC < LC, smaller size means smaller vacuum, magnet, SC ……
  - PWFA LC < LWFA LC, due to higher $\eta_{\text{wall plug}\rightarrow\text{driver}}$ and $\eta_{\text{driver}\rightarrow\text{trailer}}$
  - PBA's estimation is not as accurate as conventional LC, and should be overestimated / based on future technology
- Construction
  - PBA's cost is in a big range due to technique uncertainty
  - May not be ready in the next 20 yrs