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

IHEP PBA study status

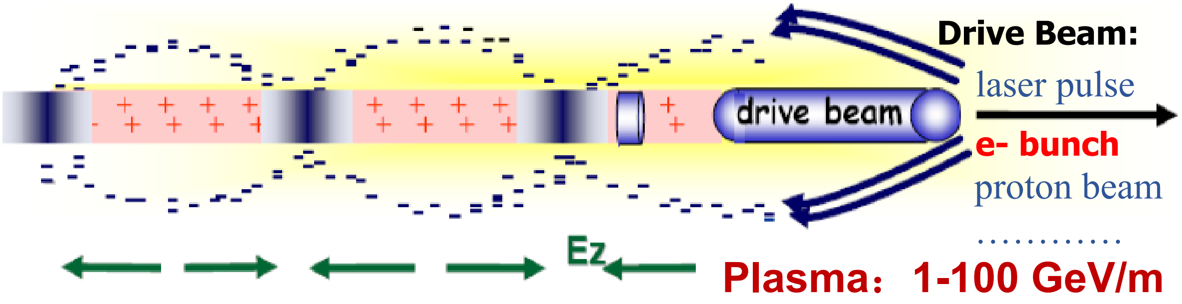
(2017——2024)

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

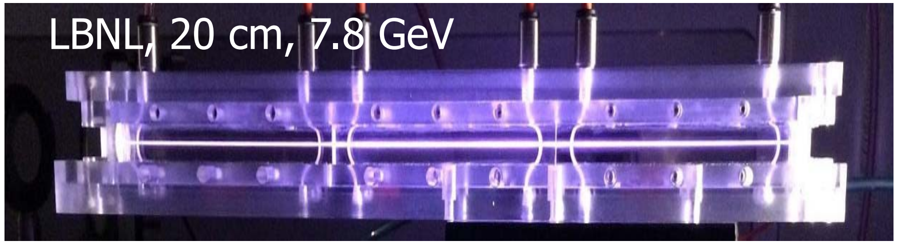
Outlines

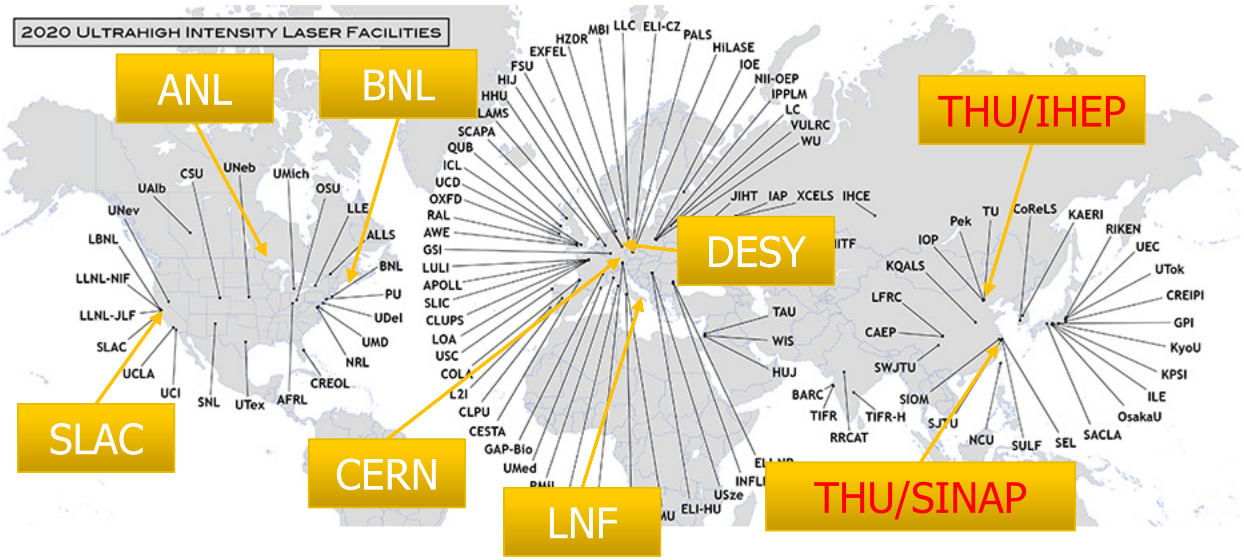
- Introduction
- PWFA and CEPC plasma injector (CPI)
- Recent LWFA studies at IHEP
- IHEP PBA TF proposals and current status
- Summaries and prospects

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



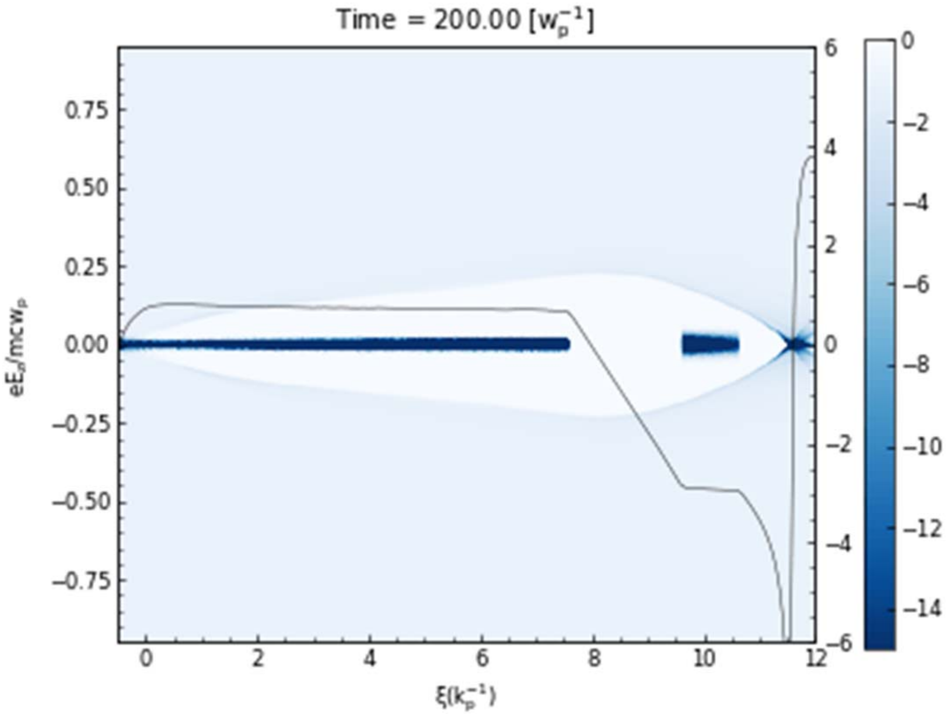
- Table-top X/γ sources
- High Energy colliders
- HEDP platforms

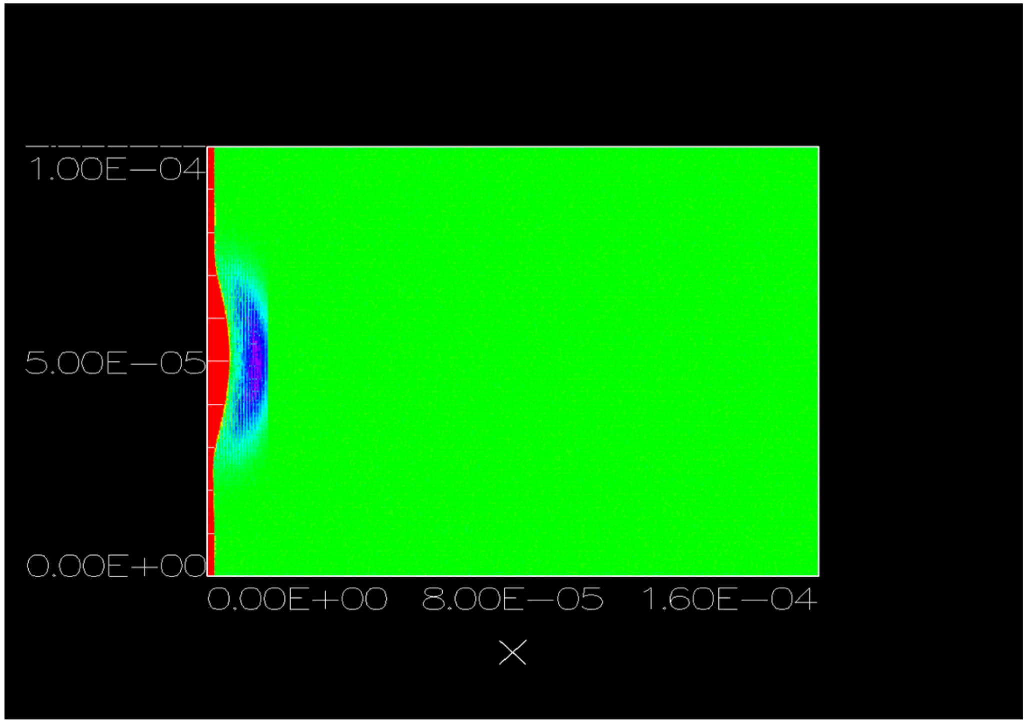




Affiliations/institutes on PWFA Study

Plasma/Laser wakefield accelerator (PWFA/LWFA)

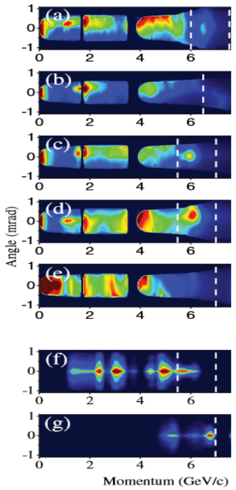


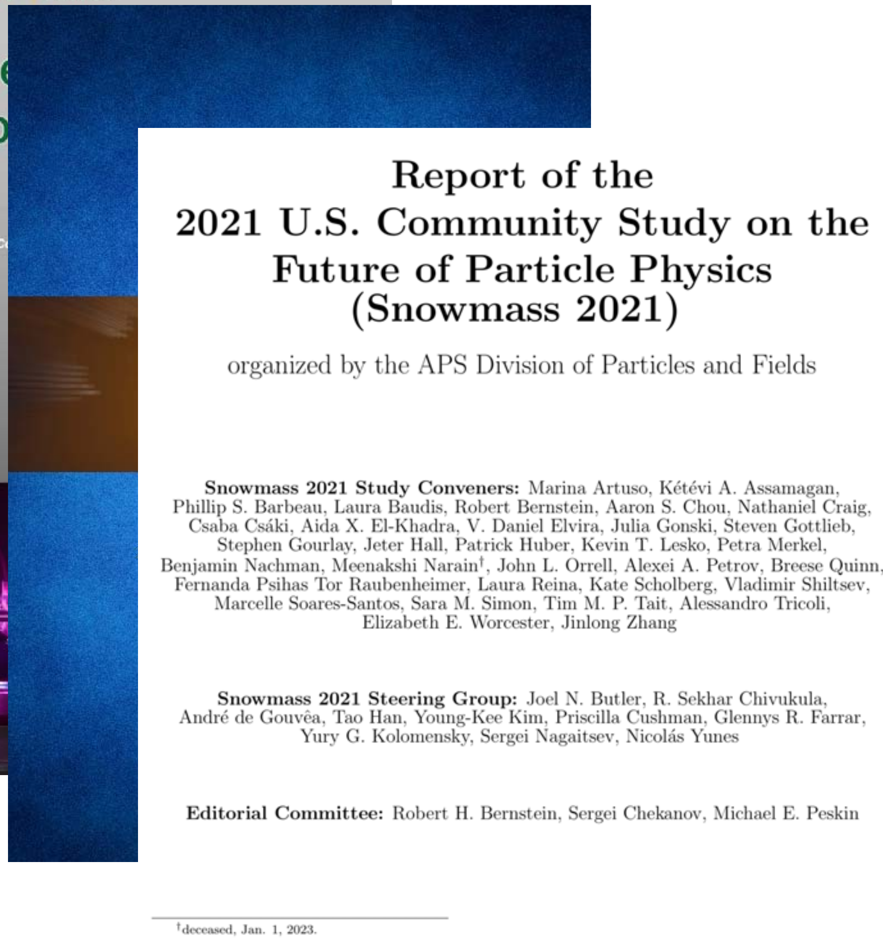


- **Driver: Conventional Accelerator**
  - **Higher average power**
  - **Higher WP to DB efficiency, DB to WB efficiency, Higher repetition rate**

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

Worldwide attentions & great progress in the last 20 years





Report of the
2021 U.S. Community Study on the
Future of Particle Physics
(Snowmass 2021)

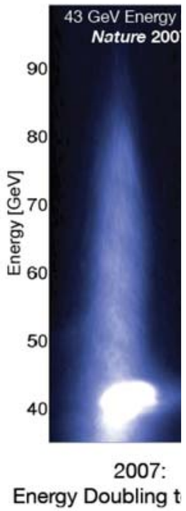
organized by the APS Division of Particles and Fields

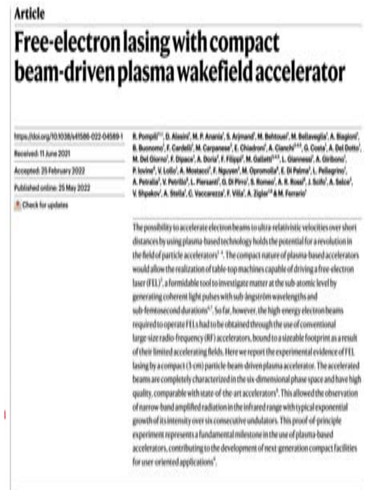
Snowmass 2021 Study Conveners: Marina Artuso, Kétévi A. Assamagan, Phillip S. Barbeau, Laura Baudis, Robert Bernstein, Aaron S. Chou, Nathaniel Craig, Csaba Csáki, Aida X. El-Khadra, V. Daniel Elvira, Julia Gonski, Steven Gottlieb, Stephen Gourlay, Jeter Hall, Patrick Huber, Kevin T. Lesko, Petra Merkel, Benjamin Nachman, Meenakshi Narain†, John L. Orrell, Alexei A. Petrov, Breese Quinn, Fernanda Psihas Tor Raubenheimer, Laura Reina, Kate Scholberg, Vladimir Shiltsev, Marcelle Soares-Santos, Sara M. Simon, Tim M. P. Tait, Alessandro Tricoli, Elizabeth E. Worcester, Jinlong Zhang

Snowmass 2021 Steering Group: Joel N. Butler, R. Sekhar Chivukula, André de Gouvêa, Tao Han, Young-Kee Kim, Priscilla Cushman, Glennys R. Farrar, Yury G. Kolomensky, Sergei Nagaitsev, Nicolás Yunes

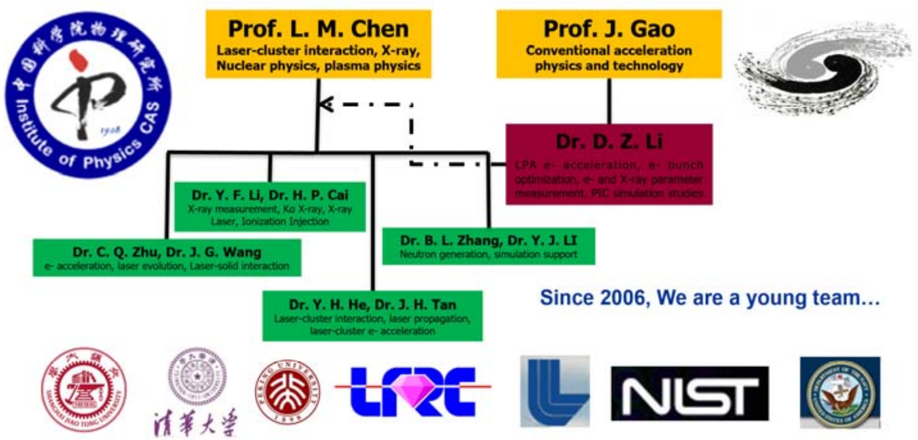
Editorial Committee: Robert H. Bernstein, Sergei Chekanov, Michael E. Peskin

†deceased, Jan. 1, 2023.





IHEP PBA studies since 2005



But with a lot of help!! ☺

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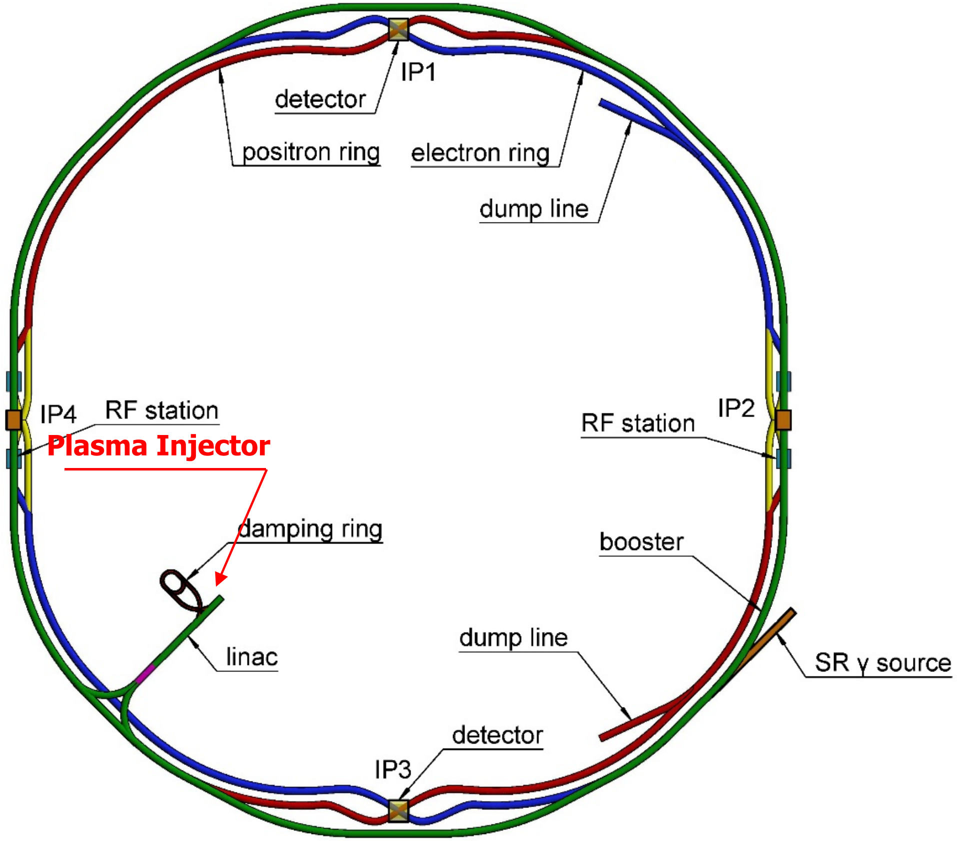
CEPC Plasma Injector (CPI)



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.

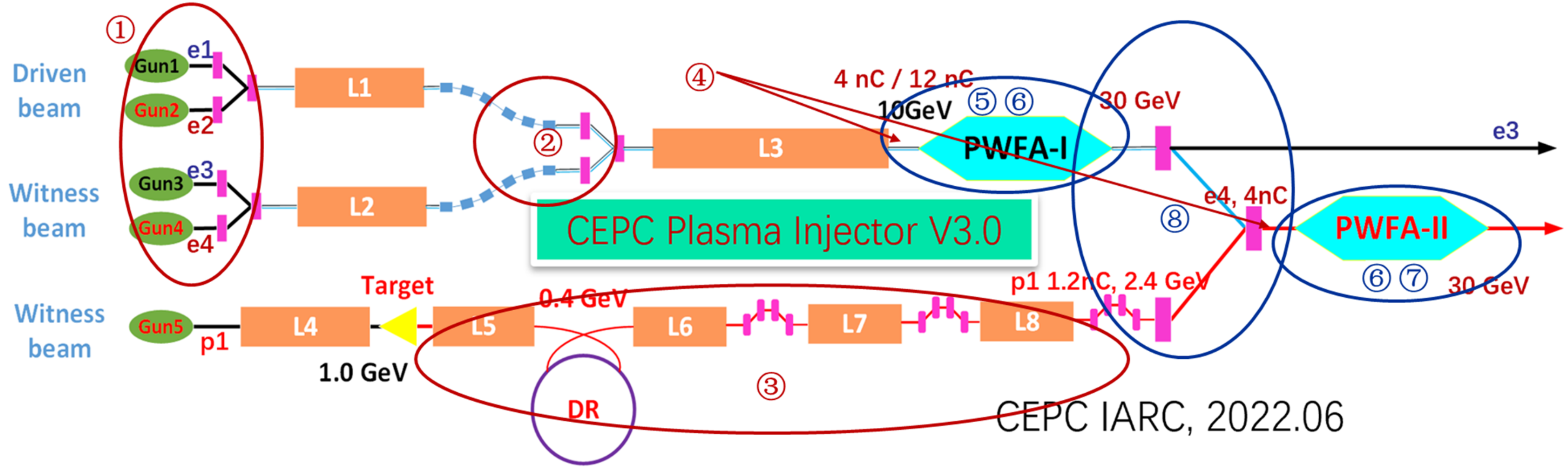
10 GeV Linac → **100 km Booster** → **Collider Rings**

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

IHEP-THU-BNU Collaborated team on CPI (since 2017)

Proposed by Prof. Gao and Prof. Lu on 2017.01
First collaborated group meeting on 2017. 03
Till now, 20+ staffs, 5 postdocs, 20+ PhD students

CPI design V3.0 and key issues for CPI



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;

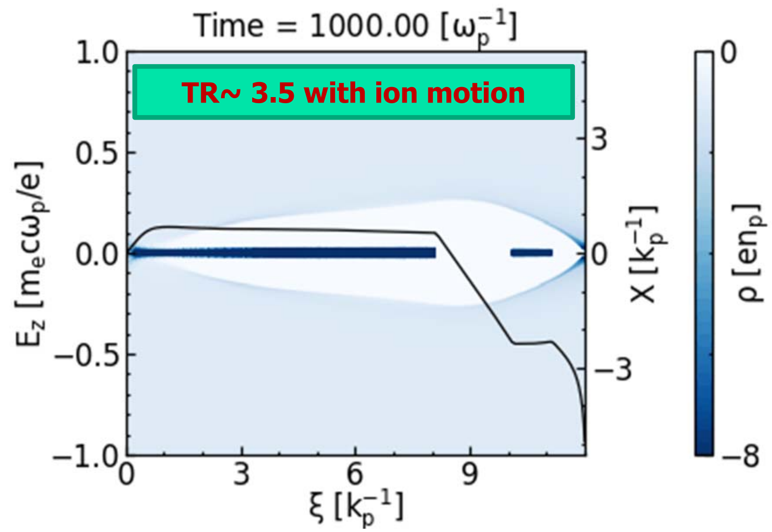
⑥ High repetition rate stable plasma sources

⑦ High quality and high efficiency e+ PWFA

⑧ Staging / Cascaded acceleration

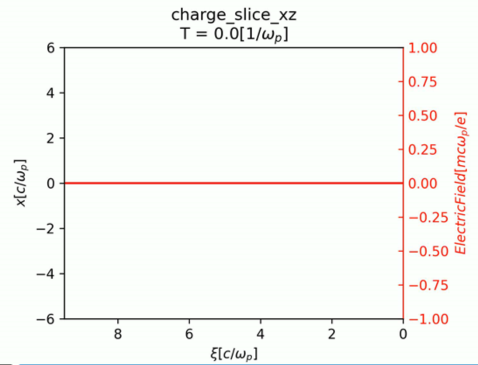
e- PWFA and long distance acc. hosing instability

Hosing instability, by Prof. Weiming An

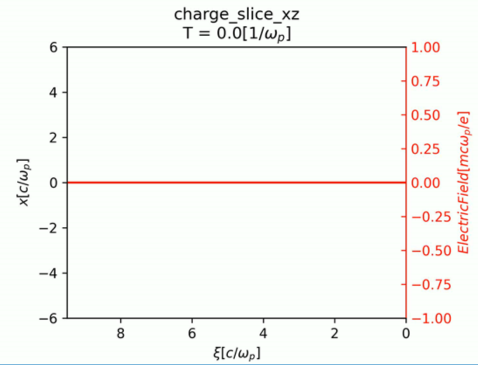


- In simulation, TR ~ 2 is stable enough
- Hosing instability may lead to emittance growth
- BNS damping may mitigate hosing instability, ion motion, for example
- Other damping sources exist in a real PBA, but not included in the simulations

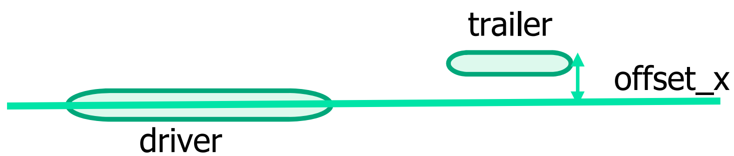
TR=2 without ion motion



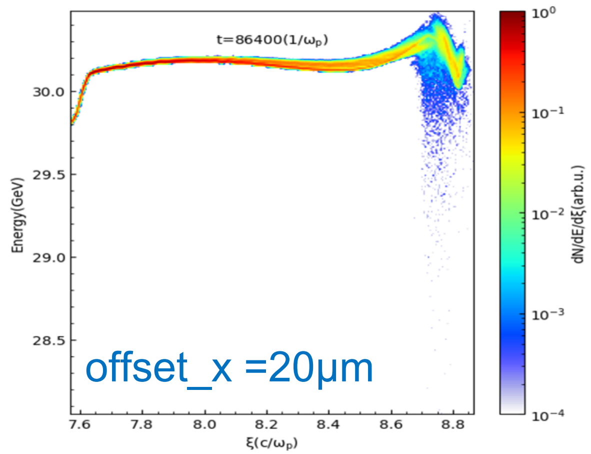
TR=2 with ion motion

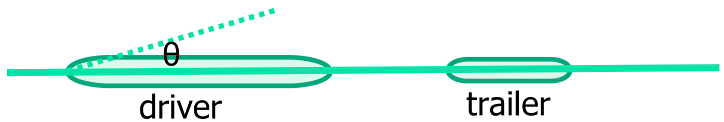


Preliminary error tolerance analysis

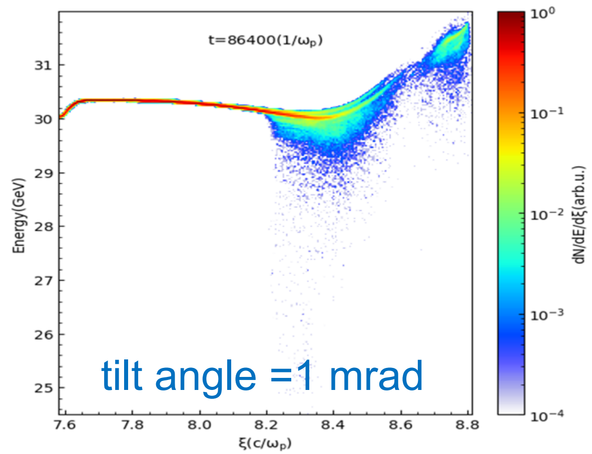


Offset (x direction)	4 μm	12 μm	20 μm	30 μm
Bunch charge [nC]	1.197	1.197	1.174	1.079
Energy [GeV]	30.01	30.04	30.16	30.37
RMS energy spread	0.43	0.41	0.22	0.72





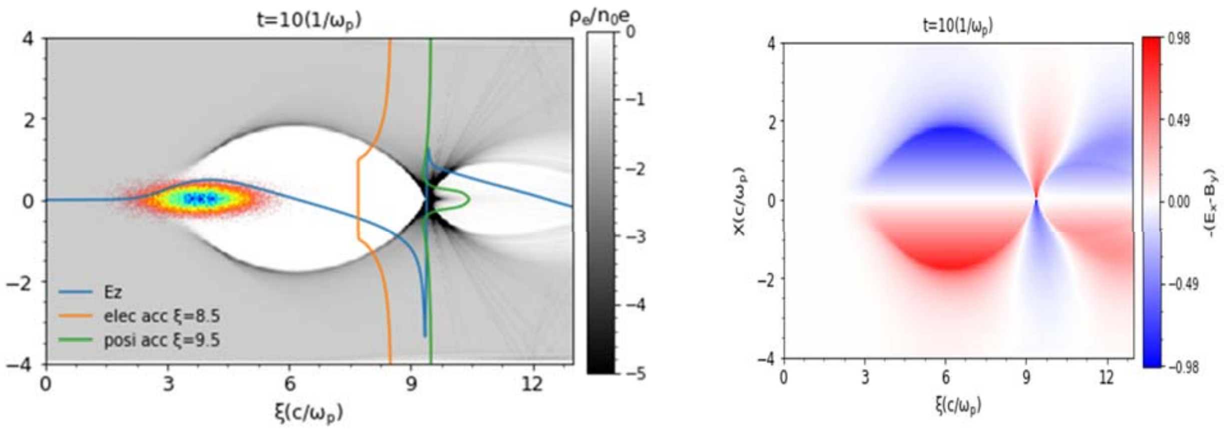
Tilt angle	10 μrad	100 μrad	1 mrad
Bunch charge [nC]	1.197	1.197	0.903
Energy [GeV]	30.01	30.01	30.24
RMS energy spread	0.41	0.41	0.65



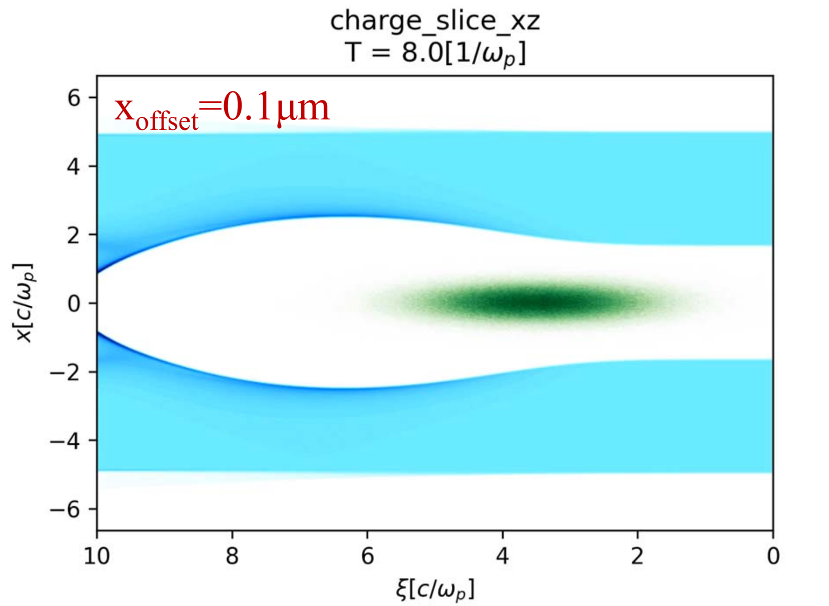
e+ PWFA studies

A "perfect" wakefield means:

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



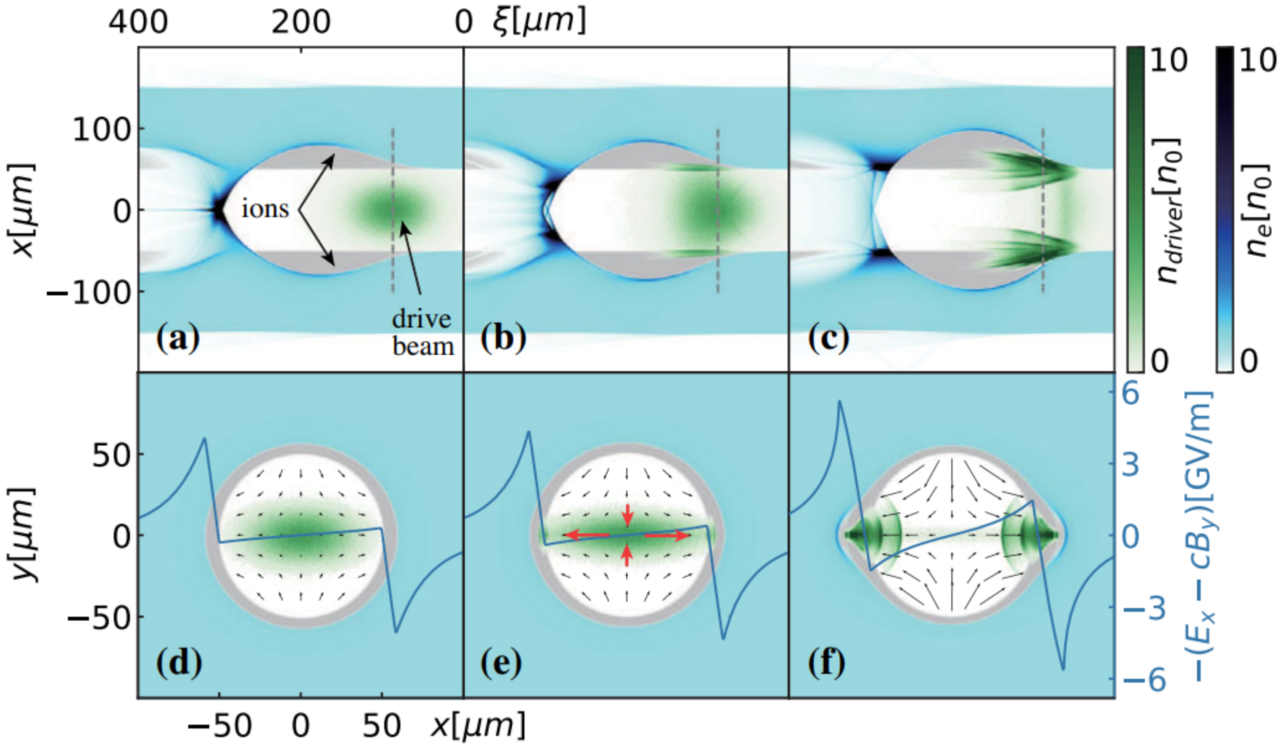
So, the blowout wakefield in uniform plasmas is quite fit for e- acceleration, while unfit for e+ acceleration

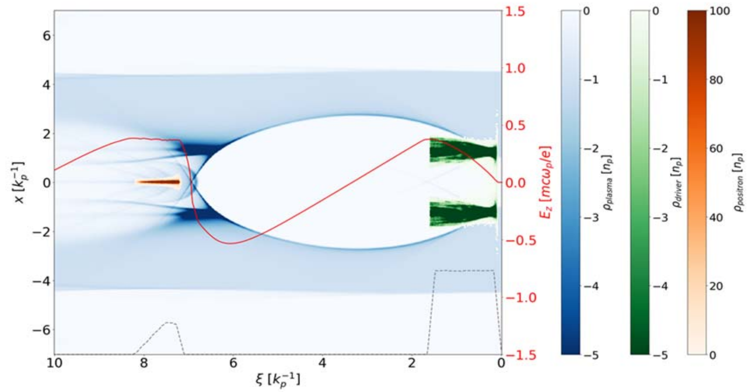


- **High efficiency 60%**
- **Low energy spread ~0.5%**
- **Small emittance growth**
- **Need e- driver, e+ trailer and plasma channel exactly coaxial**

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

e+ PWFA studies





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,*]

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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.

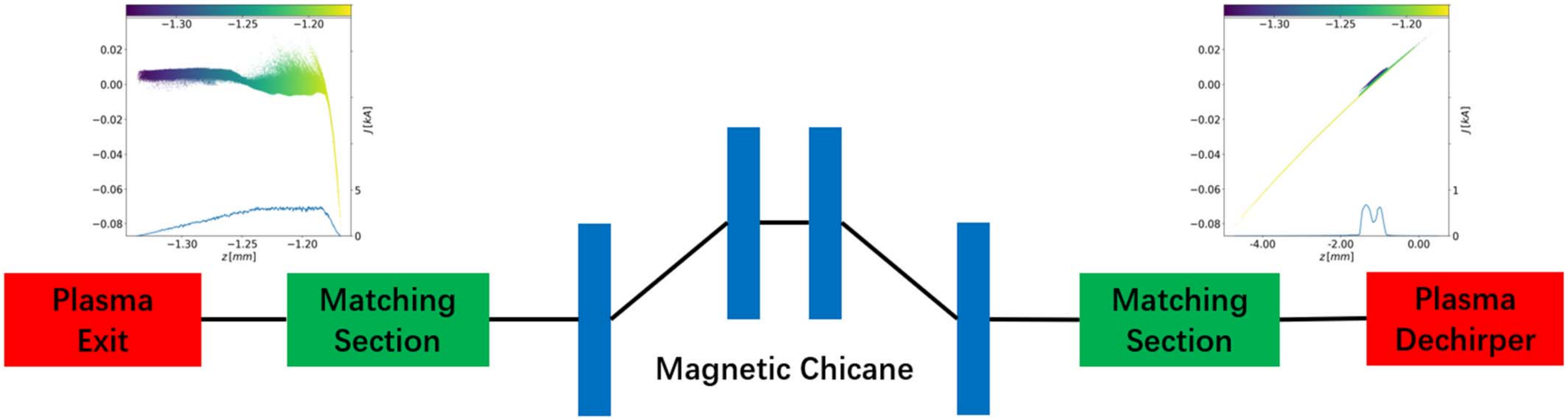
DOI: 10.1103/PhysRevLett.127.174801

e+ PWFA studies

Plasma parameters		
Density (cm^{-3})	1.133e15	
Inner radius (μm)	158	
Outer radius (μm)	711	
Beam parameters	Driver	Trailer
Charge (nC)	6.45	1.1
Energy (GeV)	30	3
Transverse size (μm)	32	6
Normalized emittance ϵ_n(mm·mrad)	32	16
Length (μm)	237	153
Energy spread δ_E(%)	0	0
Beam longitudinal distance (μm)	885	

Positron beam parameters	
Charge (nC)	1.1
Energy (GeV)	30.1
Normalized emittance ϵ_n (mm·mrad)	41.6 (x)
	18.7 (y)
Energy spread δ_E(%)	0.68
Acceleration properties	
Acceleration length (m)	20.8
Acceleration gradient (GV/m)	1.3
Beam loading efficiency (%)	22.6

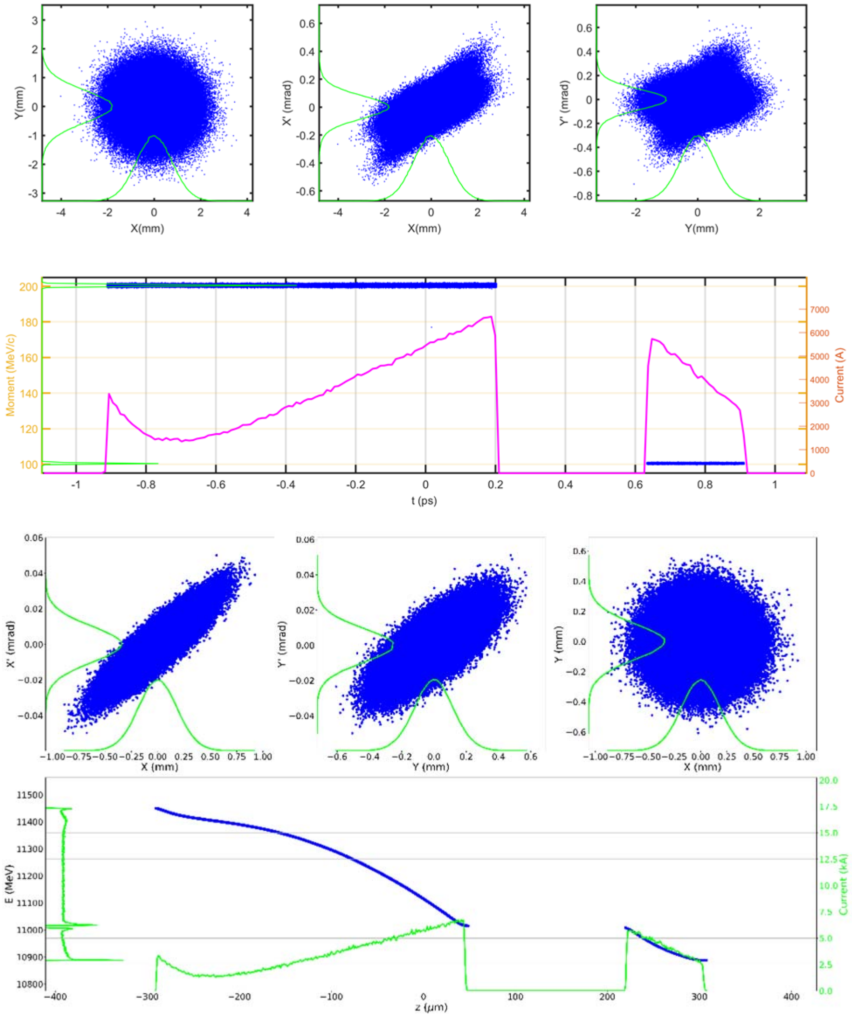
e+ PWFA studies--energy spread compression



Parameter	Symbol	Unit	Value
Beam charge	Q_{e+}	nC	1.1
Beam energy	E_{e+}	GeV	30.1
Energy spread	σ_e	%	0.68
Emittance	ε_n	mm·mrad	151(x) / 35.1(y)
Bunch length	σ_l	mm	0.322(rms)
Peak Current	I	kA	0.647

Parameter	Symbol	Unit	Value
Beam Charge	Q_{e+}	nC	1.05
Beam energy	E_{e+}	GeV	30.0
Energy spread	σ_e	%	0.156
Emittance	ε_n	mm·mrad	131 (x) 76.2 (y)

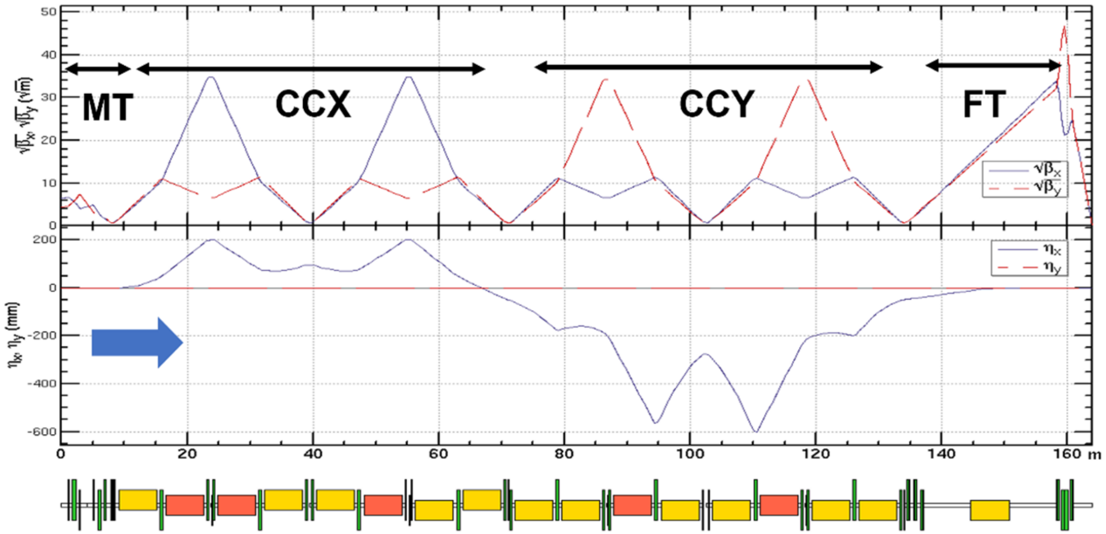
Linac design for CPI

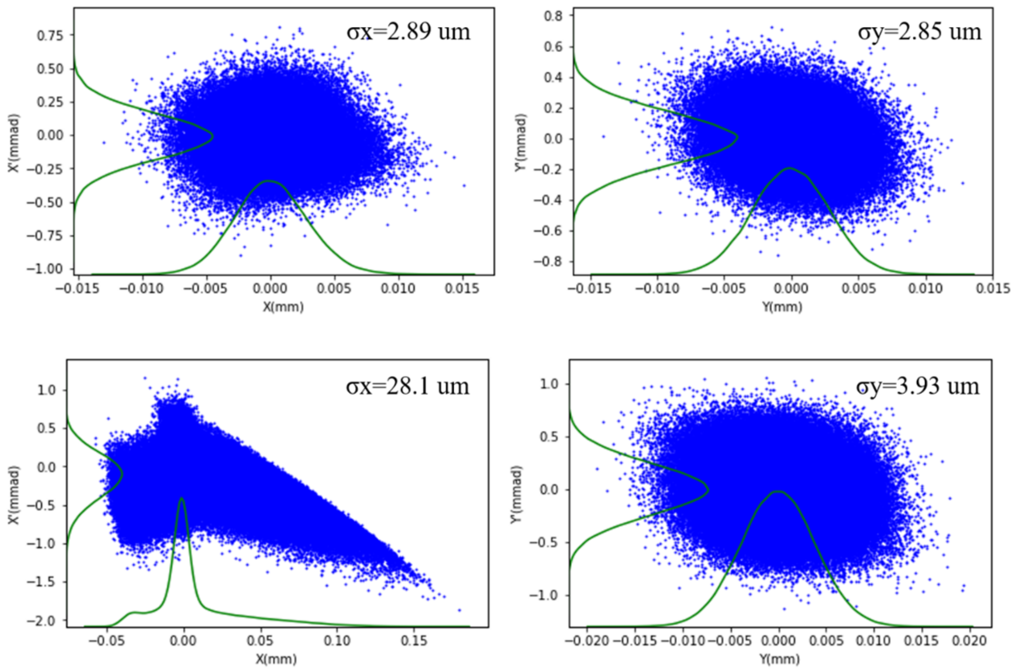


Parameter	Driver	Trailer	Total
Energy E (GeV)	11.23	10.94	11.16
Normalized emittance ϵ_n (mm-mrad) (H/V)	20.6/20.2	10.6/10.2	18.8/18.0
Bunch length (μm)	339.9	88.9	599.2
Beam size (μm) (H/V)	192/132	178/97	189/124
Charge (nC)	3.87	1.19	5.06
Energy spread	1.14%	0.34%	1.5%
Beam distance (μm)	170.4		/

Final Focus design for CPI

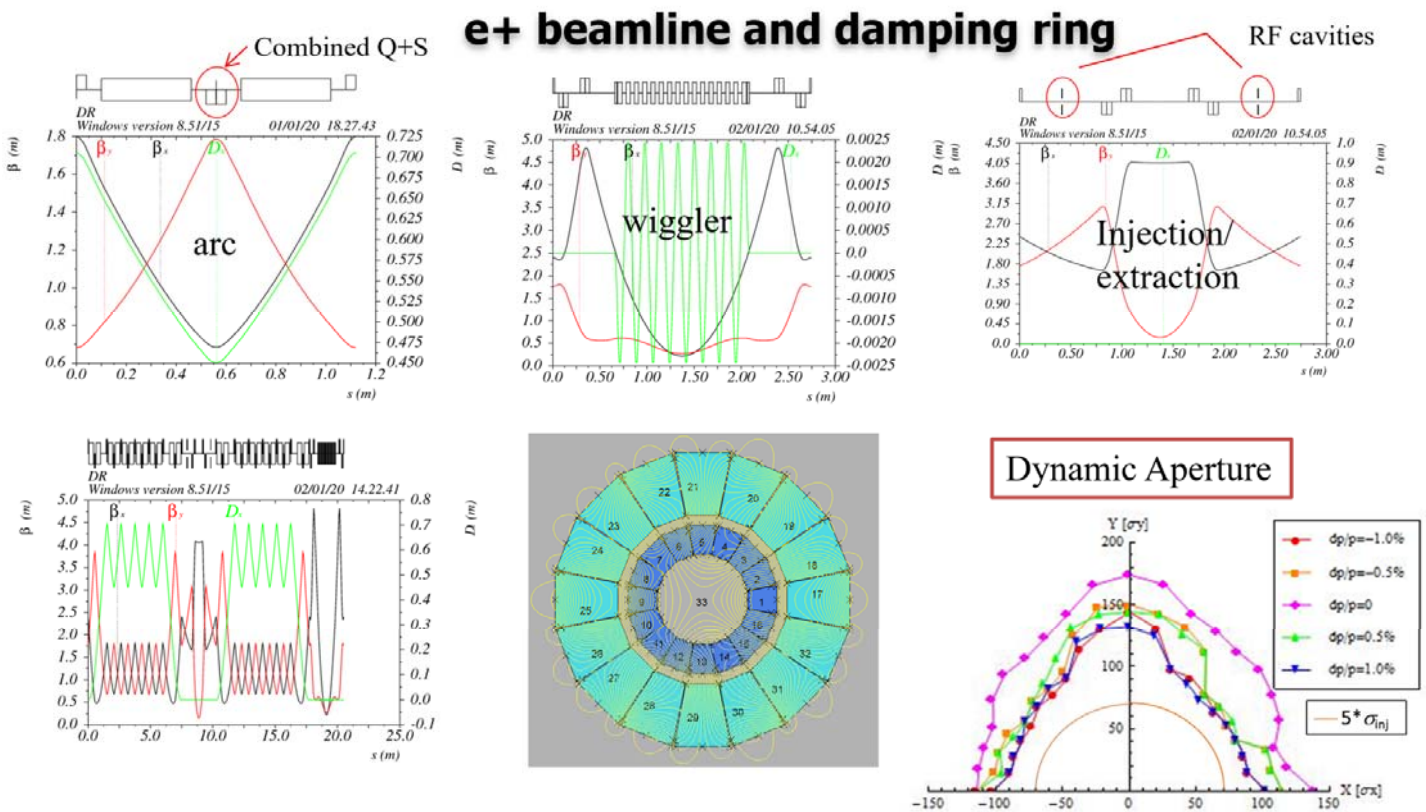
Parameter	Driver	Trailer
Energy E [GeV]	11.23	10.94
Normalized emittance ϵ_n [mm-mrad] (H/V)	20.6/20.2	10.6/10.2
Target beam size [μm]	3.89	2.75
Energy spread [%]	1.14	0.34
Beta functions at the focal point β* [cm]	1.63	
Distance from last quadrupole to the focal point L* [m]	3	





Driver's transverse emittance need further optimization. Plasma matching section as in e+ PWFA can be helpful

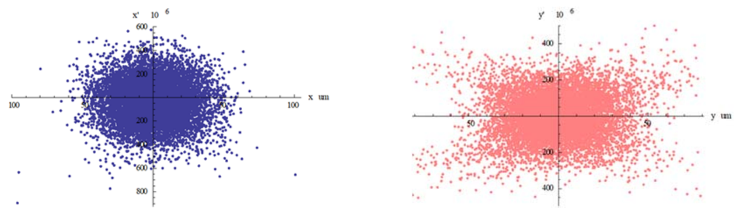
e+ beamline design for CPI



$\nu_x / \nu_y = 3.16/3.21$

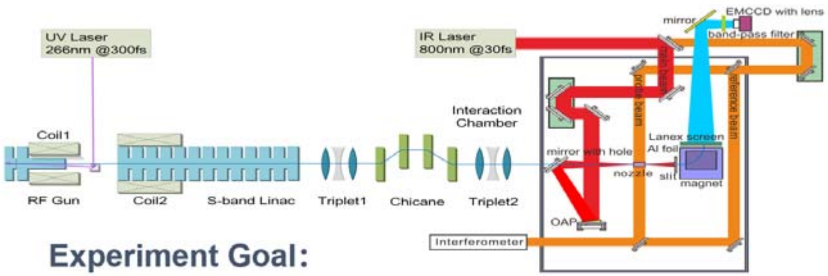
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

	BCI	BCII	BCIII
Initial energy (MeV)	400	400.1	405
δinj (%)	0.054	0.367	2.17
Initial σz (mm)	4.4	600	100
f_{RF} (GHz)	2.860	5.712	5.712
Voltage(GV)	0.0056	0.12	4.18
Gradient (MV/m)	20	40	40
L (m)	0.28	3	104
ϕ_{RF} (degree)	89	88	61.5
R_{56} (mm)	1200	27.6	5.5
Final energy(MeV)	400.1	405	2400
δext (%)	0.367	2.17	1.83
final σz (µm)	600	100	**20**



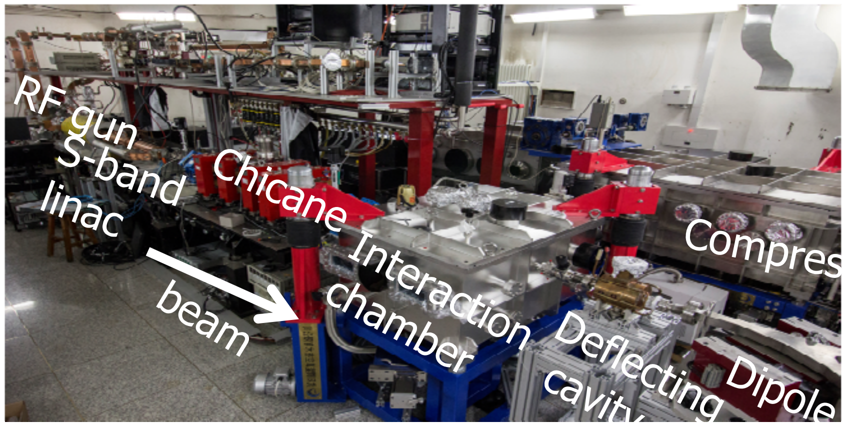
Beam distribution @ FF (~20µm)

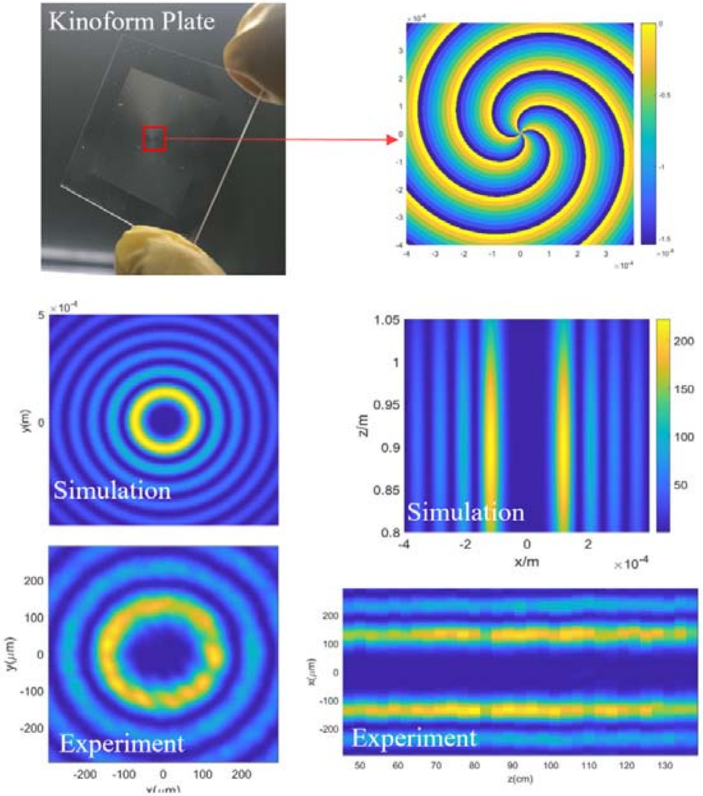
Plasma dechirper experiment → lower energy spread

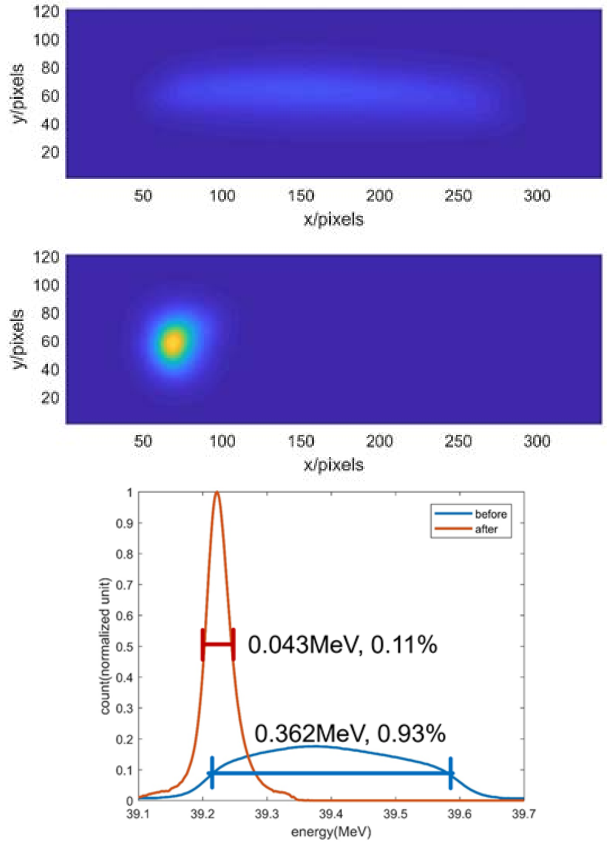


Experiment Goal:

1. **Decrease the energy spread from 1% to 0.1%**
2. **Study Hollow channel impact on beam quality**



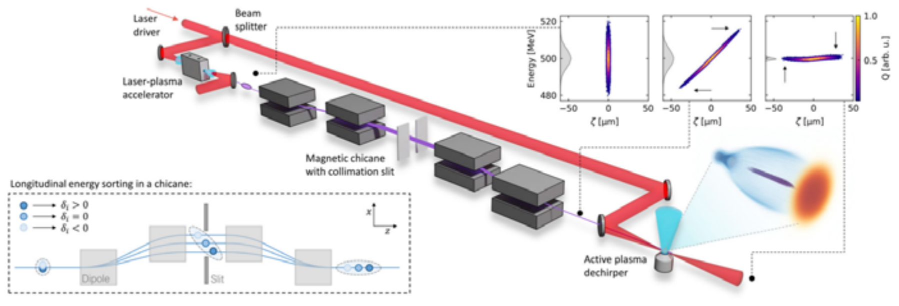




Yipeng, Wu et al., PRL 122 204804 (2019); Dr. Shuang Liu's PhD Thesis (2020)

Energy spread and stability optimization

PHYSICAL REVIEW LETTERS 129, 094801 (2022)



1-2% → ~ 0.1% @ 10 pC

Table 2. Central energy, bunch charge and energy spread of the bunches at different positions.

	LPA exit	APD exit	PPD exit
Central Energy (MeV)	490.00	494.92	476.55
	500.00	495.06	475.79
	510.00	494.88	475.54
Bunch Charge (pC)	510.00	507.98	496.54
	510.00	509.04	507.78
	510.00	507.77	506.01
Energy Spread (%)	1.20	2.28	0.55
	1.20	2.11	0.41
	1.20	2.04	0.45

2% / 1.2% → 0.1%/0.5% @ 500 pC

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PAPER

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Energy stabilization of high-charge bunches from laser plasma accelerators

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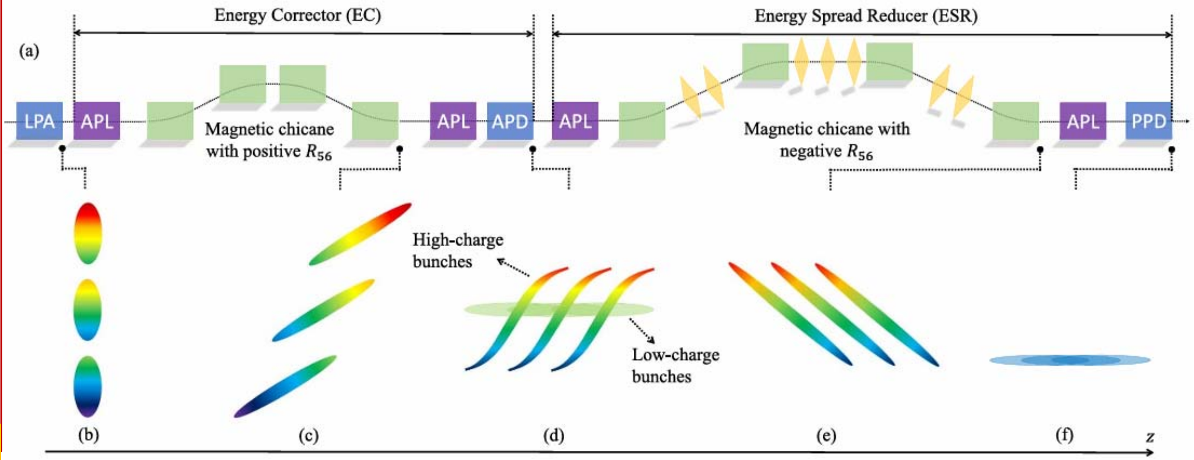
Keywords: plasma acceleration, accelerator physics, beam transport



Progress on key issues of CIP

Key issues		Preliminary study/ Conceptual design	Detailed and convincing simulations / designs	Experiment test / Prototype
e- PWFA	HTR	√	√	×
	Beam quality preservation	√	√	×
	Error analysis	√	×	×

Biggest uncertainty: lack of experimental test

Need a dedicated PWFA test facility for CPI!

Conv. acc. physics and techniques	Beam merging	√	×	×
	Instrumentation	√	×	×
	Timing synchronization	√	×	×
	Positron beamline	√	√	×
Plasms source and beam manipulation	Plasma dechirper	√	√	√
	Plasma lens	×	×	×
	Plasma sources	√	√	×
	Staging	√	×	×

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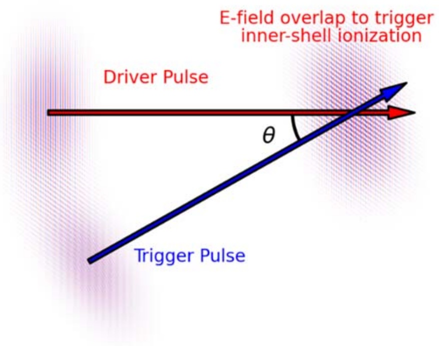
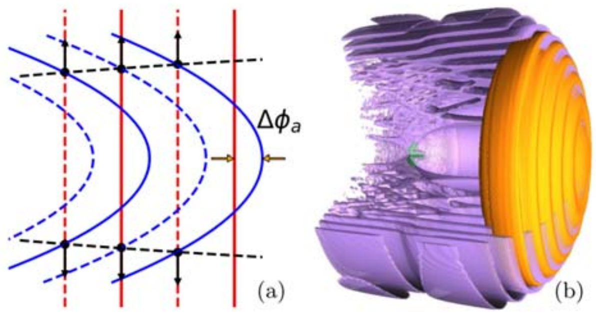
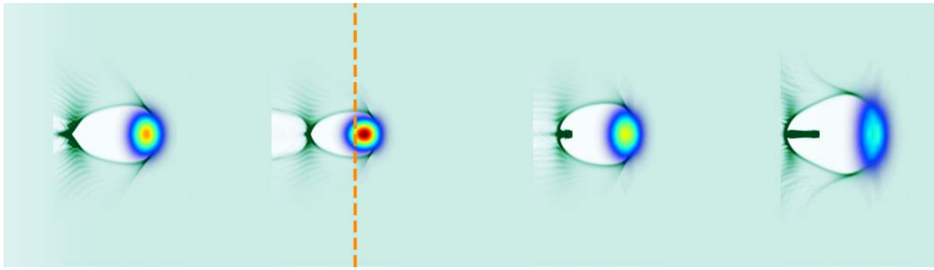
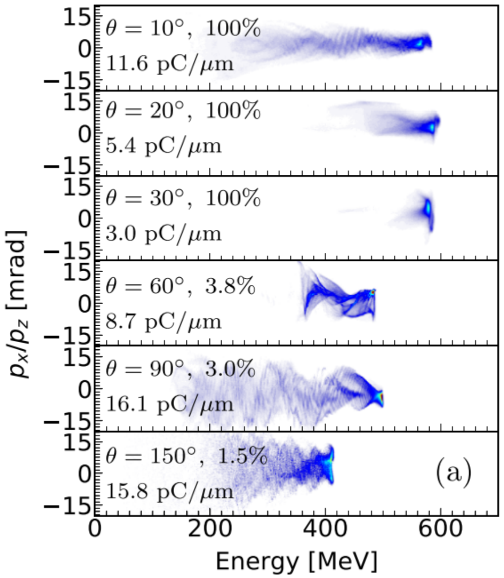
Injection Scheme study @ IHEP → eff. ↑ energy spread ↓

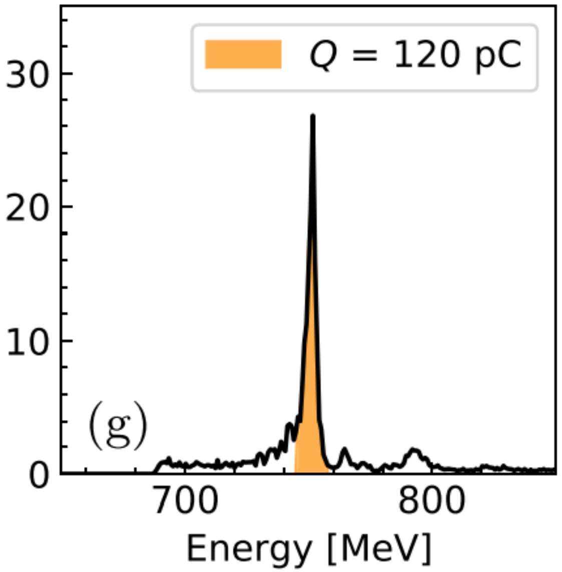




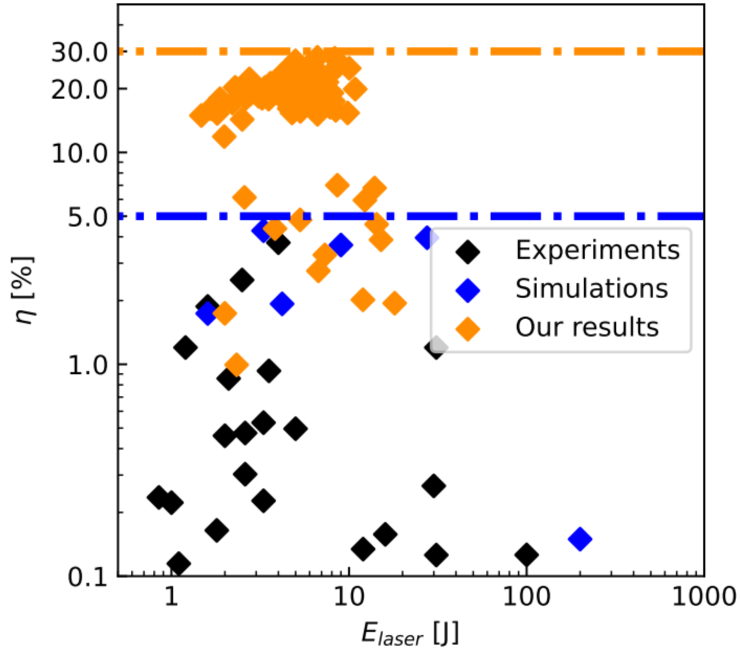




PPCF 64, 45012 (2022)



MRE 7, 054001 (2022)

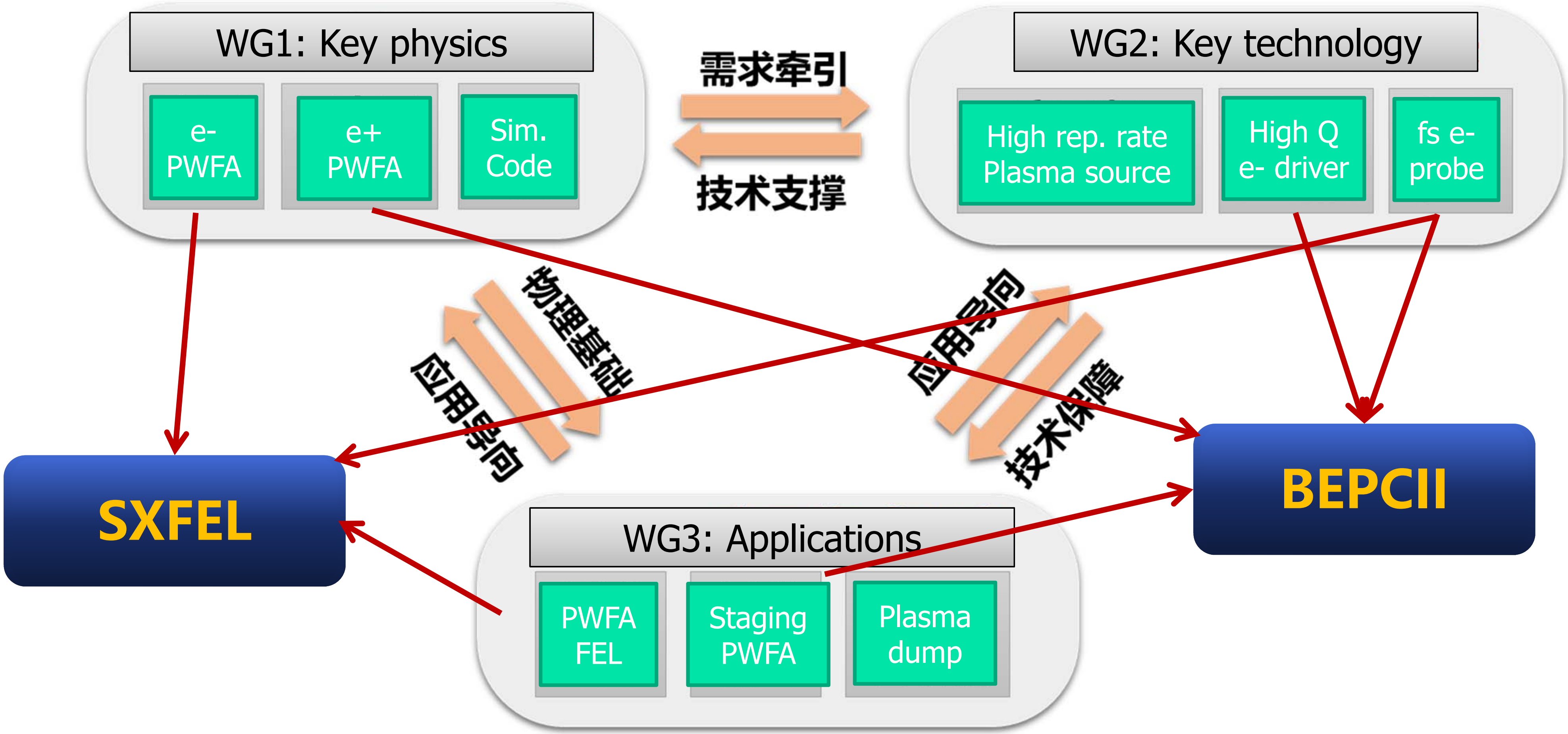


PRAB 26, 091303 (2023)

Outlines

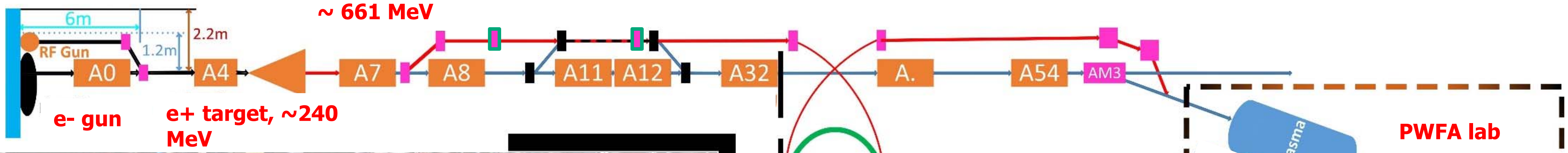
- Introduction
- PWFA and CEPC plasma injector (CPI)
- Recent LWFA studies at IHEP
- IHEP PBA TF proposals and current status
- Summaries and prospects

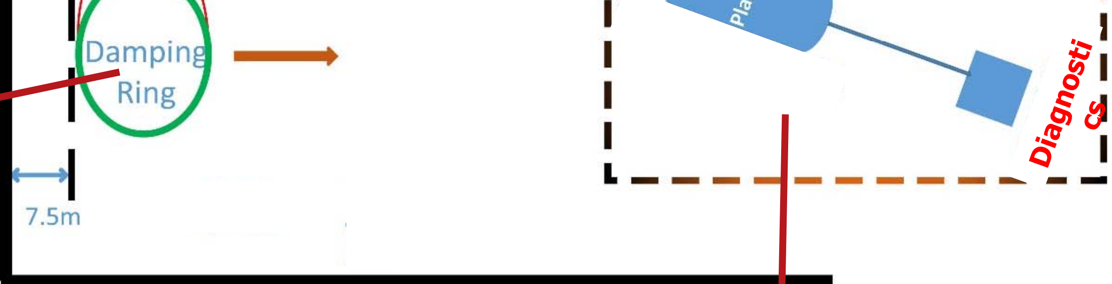
CAS program on PWFA (approved in sept. 2023, 90M RMB)

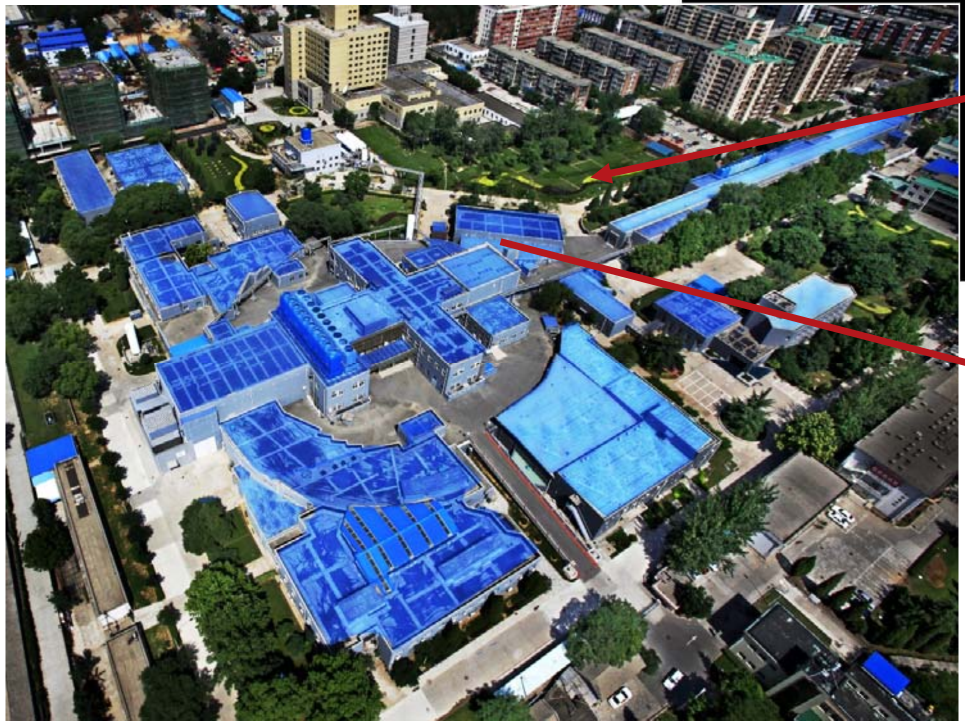


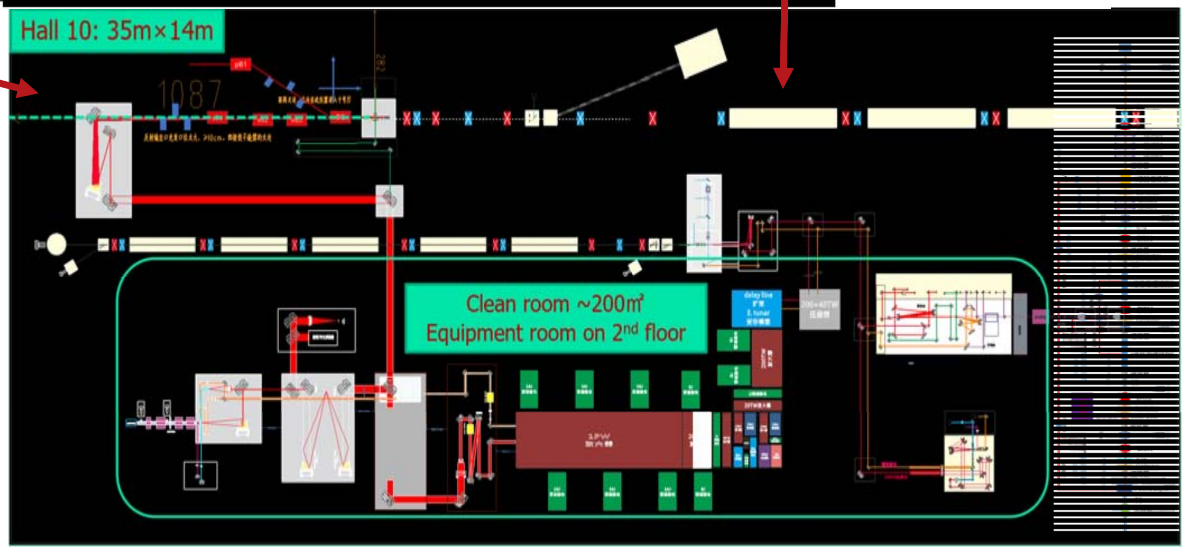
Hall #10 @ IHEP was used for detector calibration

Test facility based on BEPCII linac design V1.0



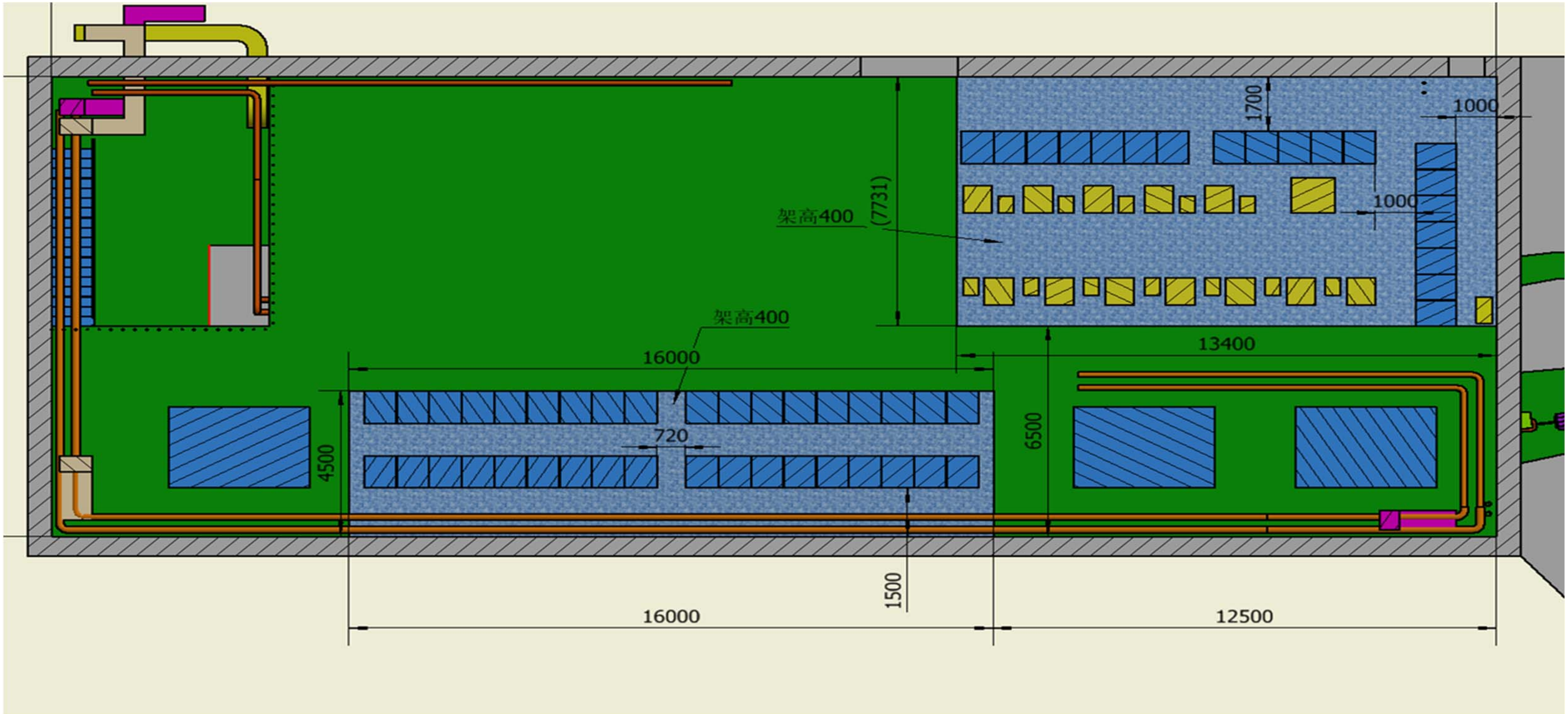






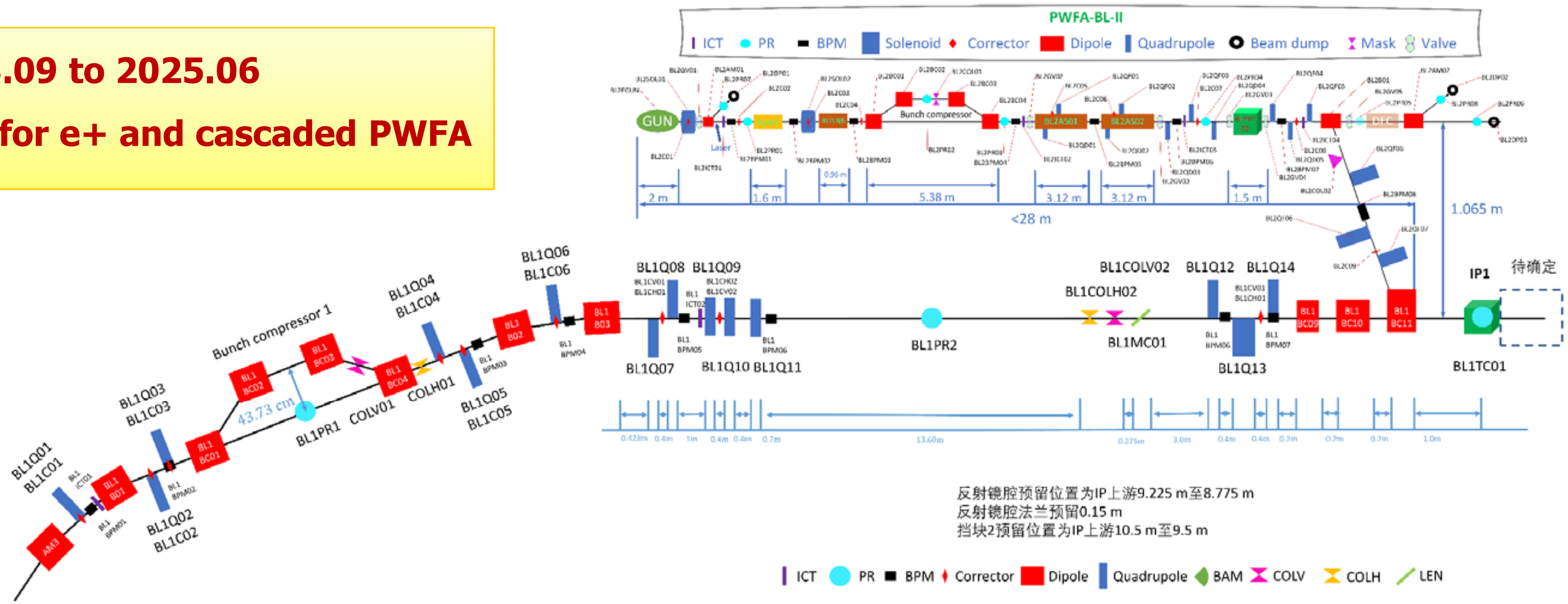
2.5 GeV e-/e+ beamline + PW-level high performance laser system

Test facility based on BEPCII linac design V2.0



Detailed beamline design V3.0

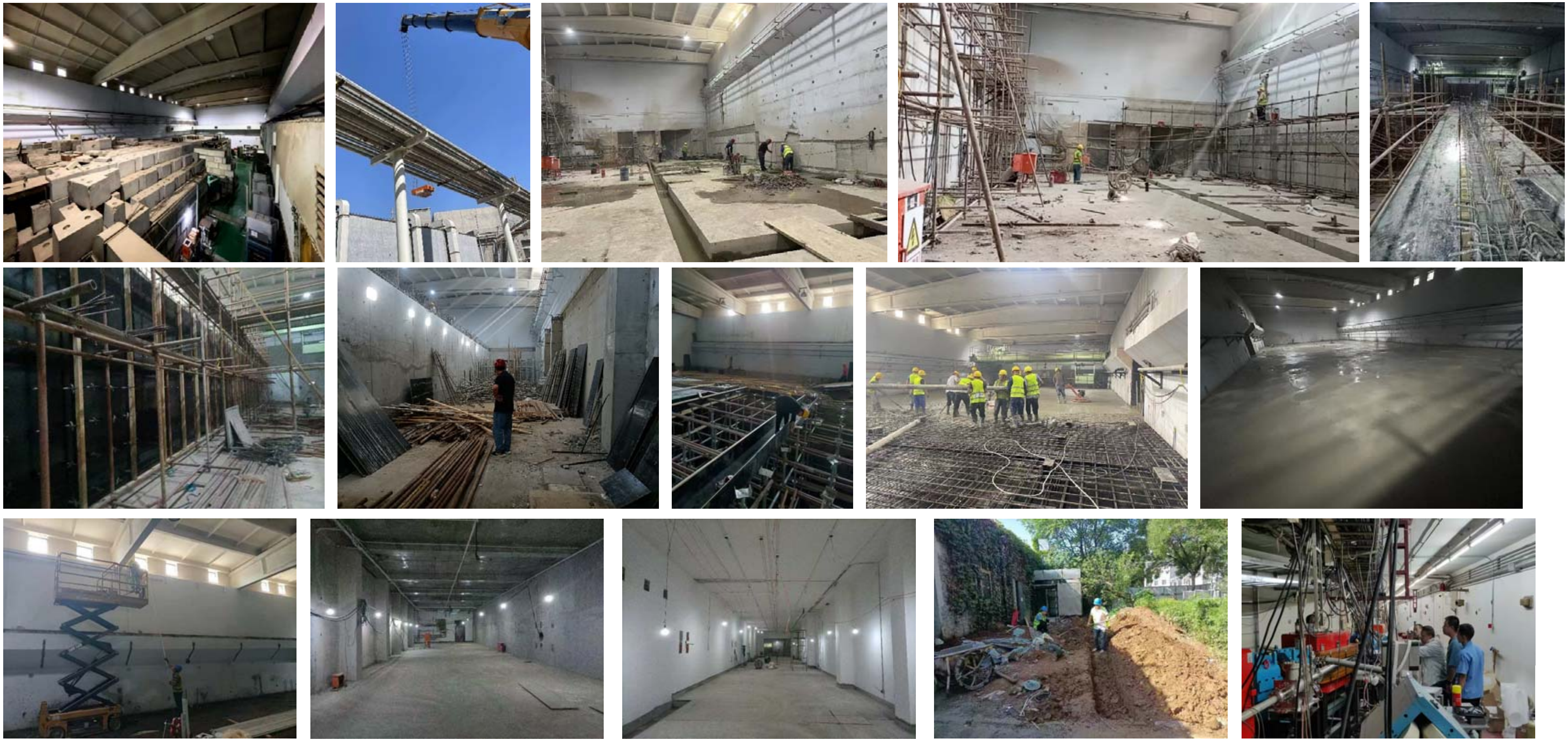
- **From 2023.09 to 2025.06**
- **Unique TF for e+ and cascaded PWFA**



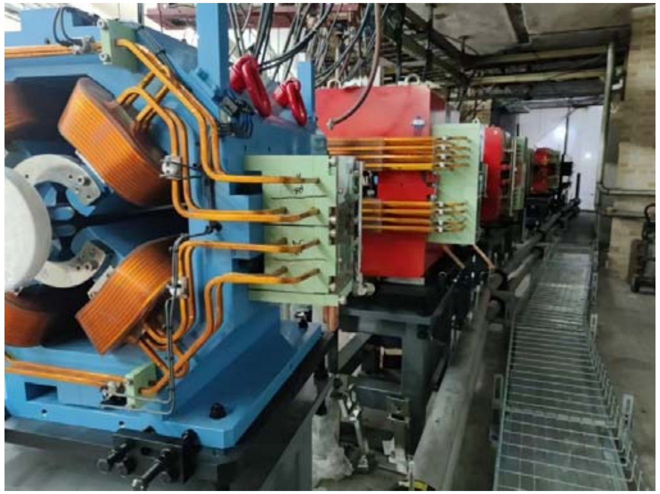
① **L-band e- Gun (> 5 nC): ~ CPI requirement**
② **Beams combination: similar to CPI**
③ **High quality e+ beam: NO**
④ **Final Focus: even harder than CPI**

⑤ **HTR e- acc.: easier than CPI (~CPI @ SXFEL)**
⑥ **High rep. rate plasma source: > CPI**
⑦ e+ PWFA acc.: 1st exp. result, < CPI
⑧ Cascaded/staging: 1st exp. result, < CPI

Lab construction and beamline installation is ongoing



Lab construction and beamline installation is ongoing



Outlines

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Test facility based on BEPCII linac

- Conceptual design of CPI has been carried out since 2017
- Simulation studies during the last 5-6 years, no showstoppers till now
- We'll focus on the TF construction in the next 2-3 years
- The new TF is NOT only for PBA, but also for conventional accelerator R&D
- The new TF is NOT only for CPI, but also for a real plasma-based accelerators

Thank you!


Thank you and welcome to IHEP