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

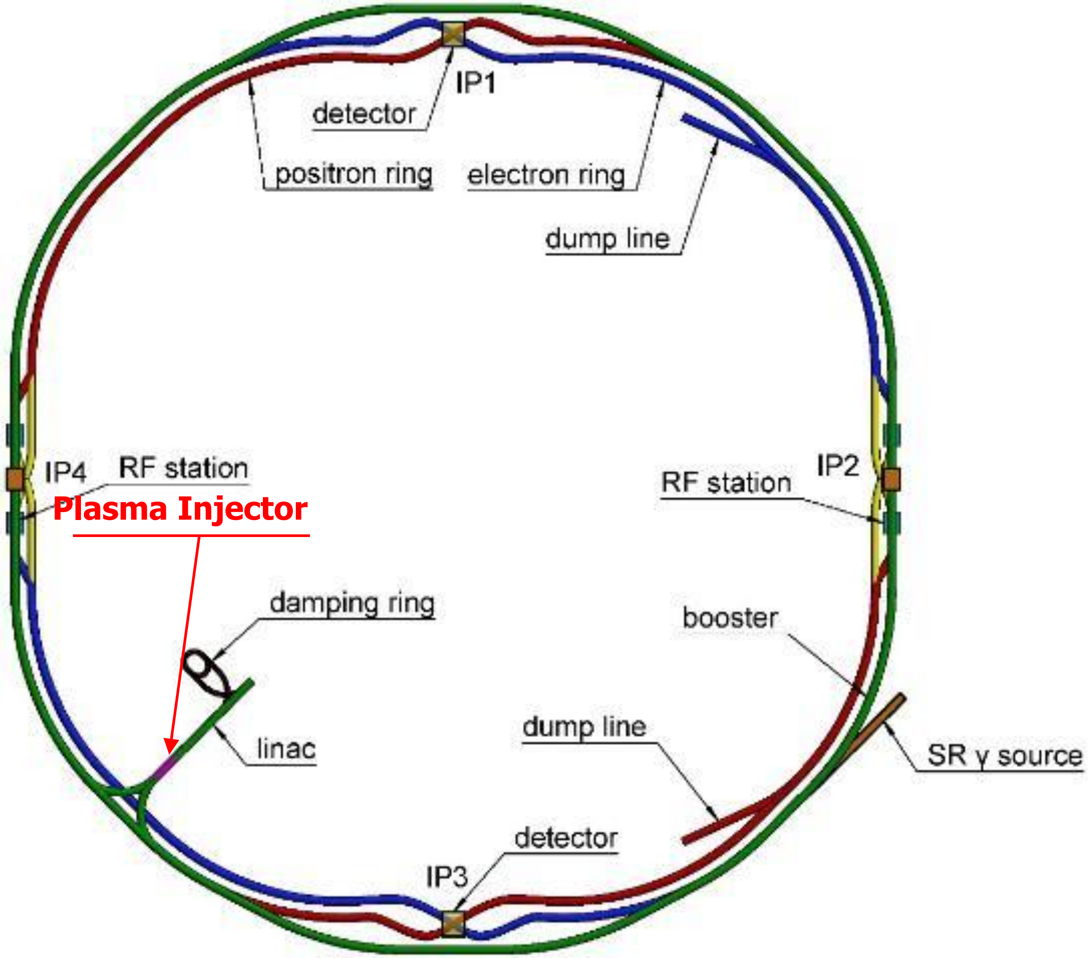
IHEP plasma accelerator test facility status

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

Outlines

- Motivation
- PBA TF based on BEPCII linac
- Proposed experiments in the near future
- Summaries and prospects

CEPC Plasma Injector (CPI)



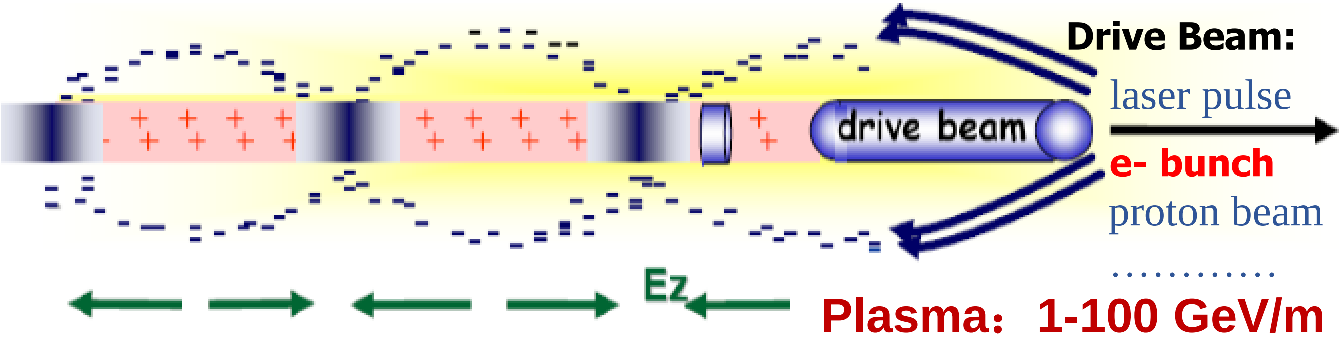
10 GeV e-/e+ beam in a 100 km ring

- 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**

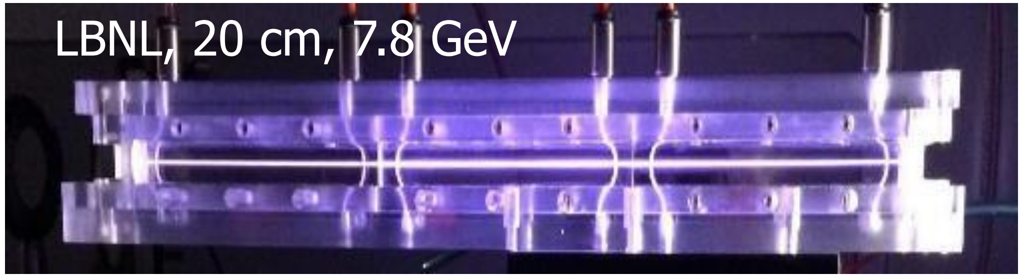
10 GeV linac + CT coil magnet, or 30 GeV linac + iron-core magnet ? Both lead to significant cost rise ~ 1 B RMB

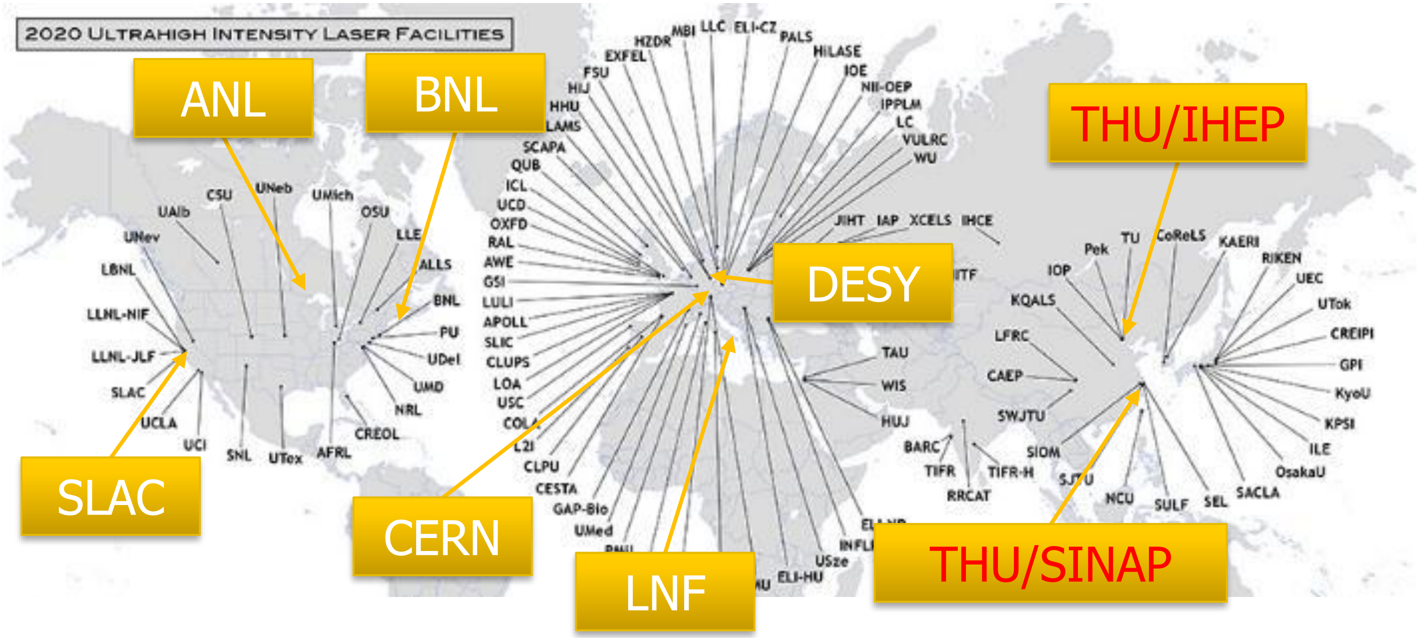
Plasma Based Acceleration (PBA): > 1000 $E_{acc.}$



Plasma: 1-100 GeV/m

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

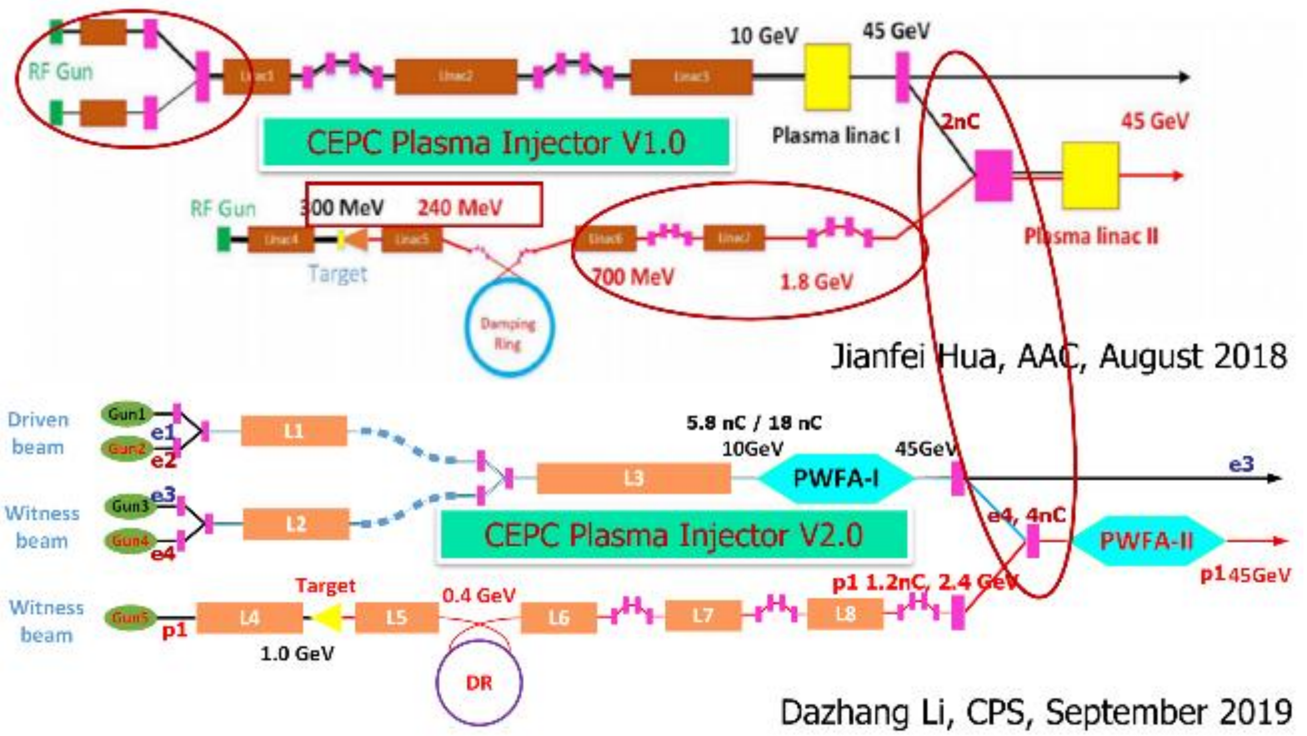




Affiliations/institutes on PWFA Study

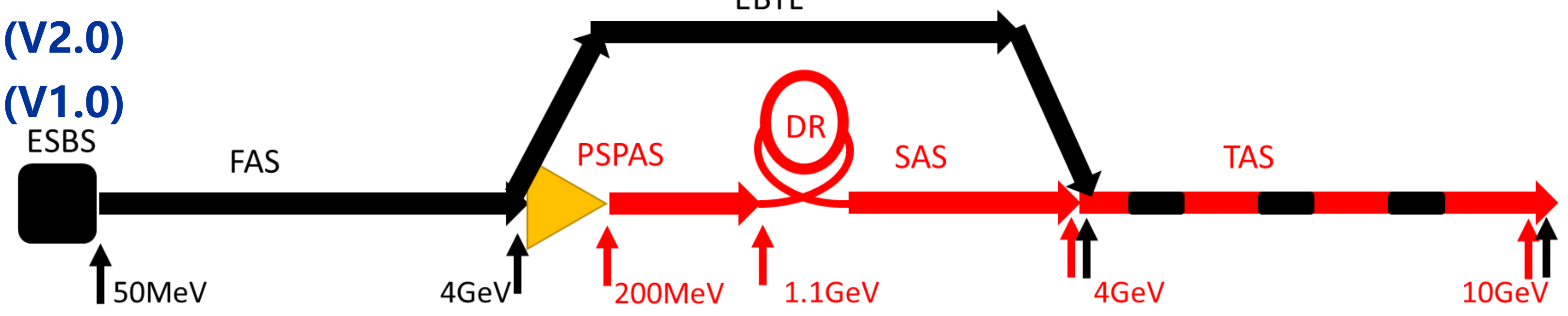
CPI requirement at CEPC CDR stage

Booster Requirement	
Energy (GeV)	45.5
Bunch Charge (nC)	0.78
Bunch length(um)	<3000
Energy Spread(%)	0.2
ε_N(μm·rad)	<800
Bunch Size(um)	<2000



Principles for CPI design V1.0 and V2.0:

- Main linac: 10GeV S-band
- L-band (10+ nC) and S-band (≤5nC) RF guns
- Compressed and then combined (V2.0)
- Combined and then compressed (V1.0)
- Different e+ acc. scheme
- e+ PWFA need to be cascaded
- e- PWFA with TR ~ 3.5

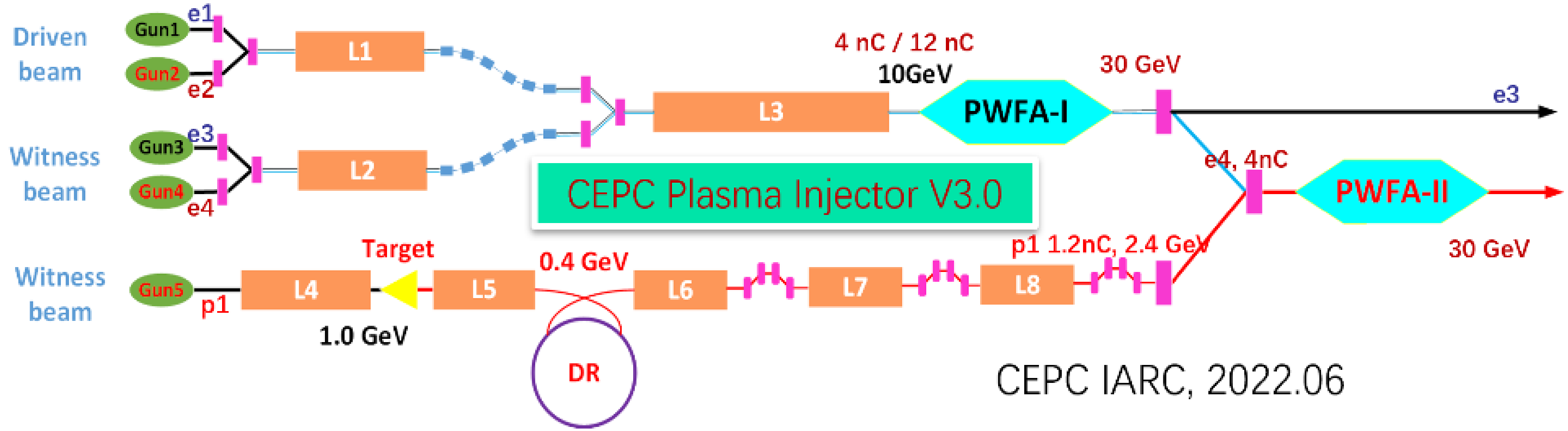


CPI requirement at CEPC TDR stage

Parameter	Symbol	Unit	Requirement
e^- /e^+ beam energy	E_{e-}/E_{e+}	GeV	30
frequency	f_{rep}	Hz	100
e^- /e^+ bunch population	N_{e-}/N_{e+}	nC	> 1.0
Energy spread (e^- /e^+)	σ_e		$< 2\times10^{-3}$
Emittance (e^- /e^+)	ε_r	nm· rad	< 10
Bunch length (e^- /e^+)	σ_l	mm	0.2~ 2
Switch time e^- /e^+		s	< 2
Energy stability			$< 2\times10^{-3}$
Longitudinal stability		mm	< 2
Orbit stability		mm	<3 (H) / 3 (V)
Failure rate		%	< 1

Principles for CPI design V3.0

- Similar linac requirement with design V2.0, and the design goal still be 10 GeV → 30 GeV
- Still need L-band RF gun for 10+ nC bunch
- Not use 30 GeV linac as in TDR baseline due to
  - S + C: lower bunch charge
  - PWFA beam quality meets the requirement of booster but not good enough for collider ring
  - For full energy injection, TR > 3 or even > 5



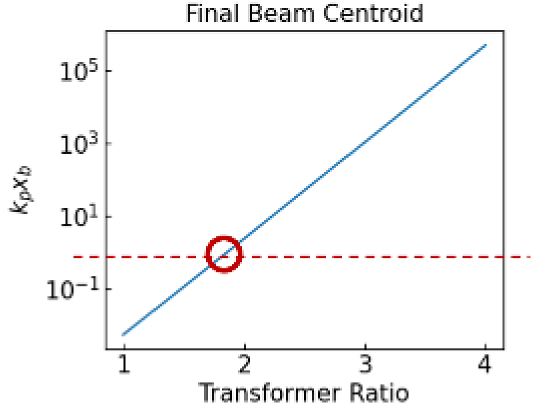
CEPC IARC, 2022.06

CPI e- PWFA for TR ~ 2 (by Dr. Shiyu Zhou)

CEPC injector's baseline was changed: 10 GeV → 30 GeV → TR ≥ 2

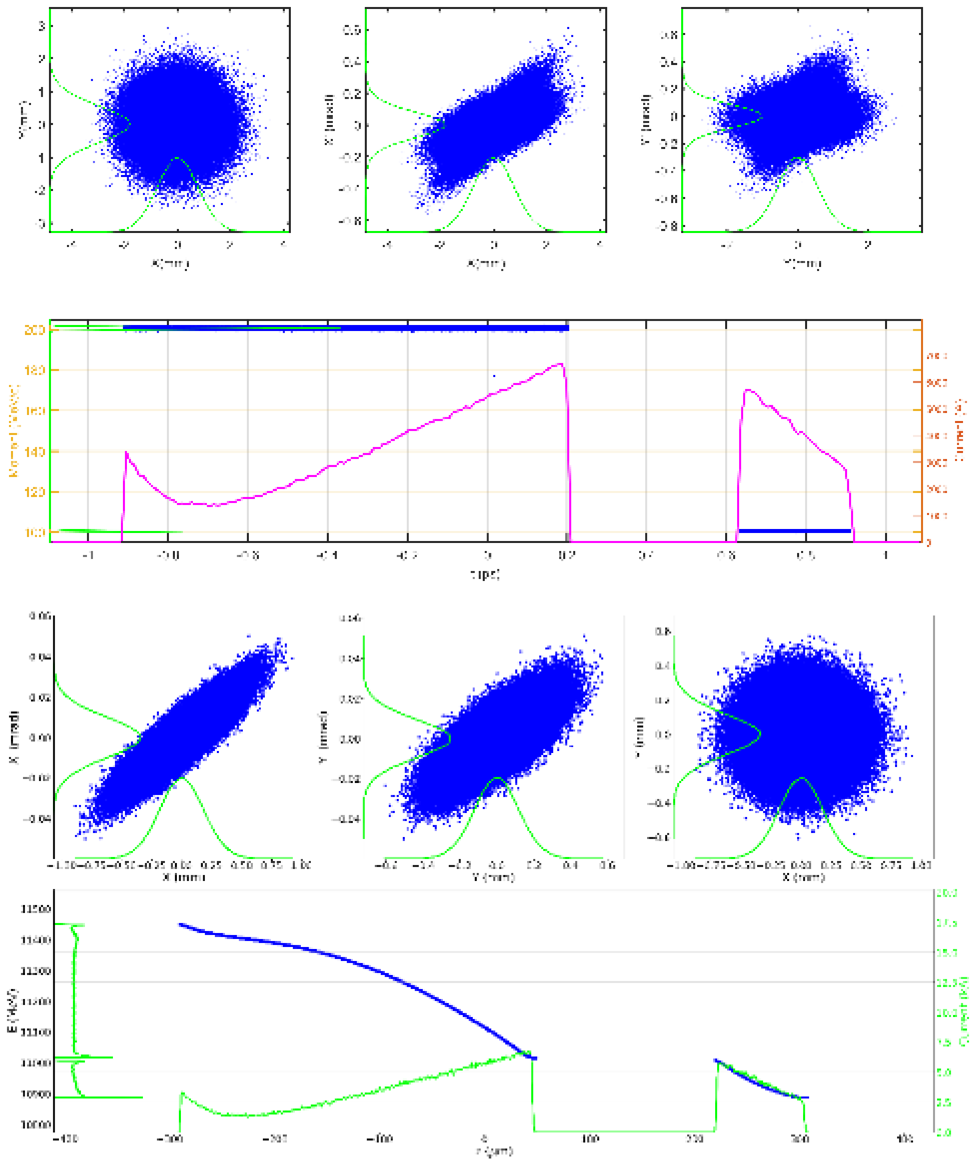
beam	Driver	Trailer
plasma density $n_p (\times 10^{16} cm^{-3})$	0.50334	
Driver energy $E(GeV)$	10	10
Normalized emittance $\epsilon_n (mm\ mrad)$	20	10
Length(um)	350	90
Spot size(um)	3.89	2.75
Charge(nC)	4	1.2
Energy spread $\delta_E (\%)$	0	0
Beam distance(um)	180	

For a 10GeV driver, beam size $k_p \sigma_r = 0.2$, c=0.7, $c_b = 0.8$



Accelerating distance (m)	6.3
Trailer energy $E(GeV)$	30.0
Normalized emittance $\epsilon_n (mm\ mrad)$	10
Charge(nC)	1.2

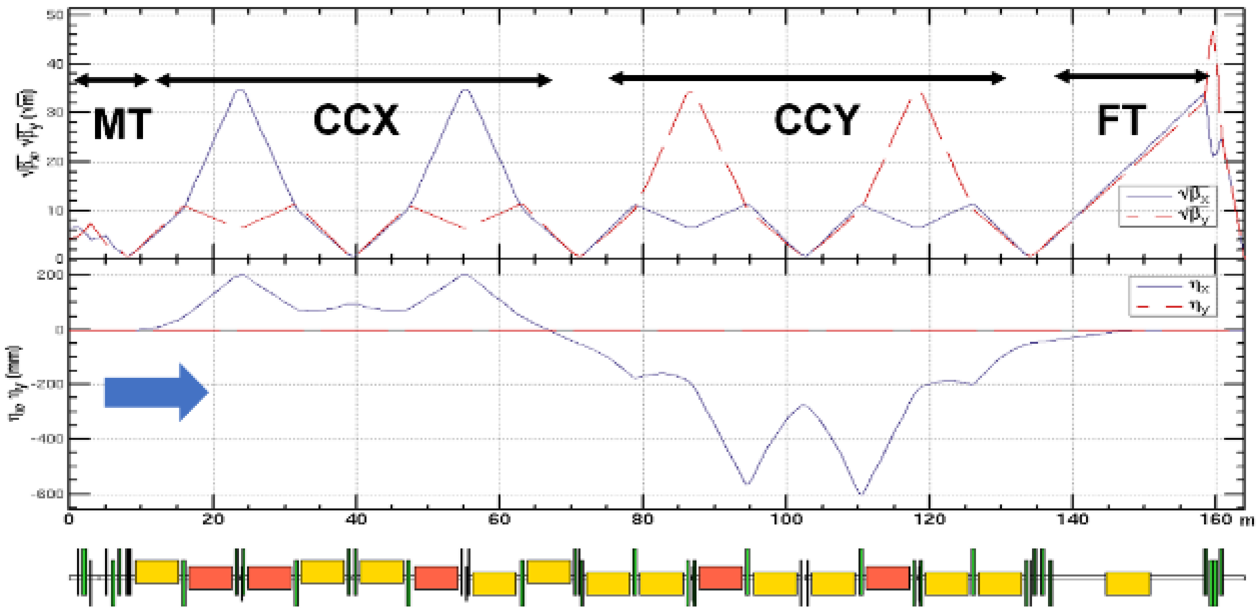
Linac design and optimization for CPI (by Dr. Cai Meng)

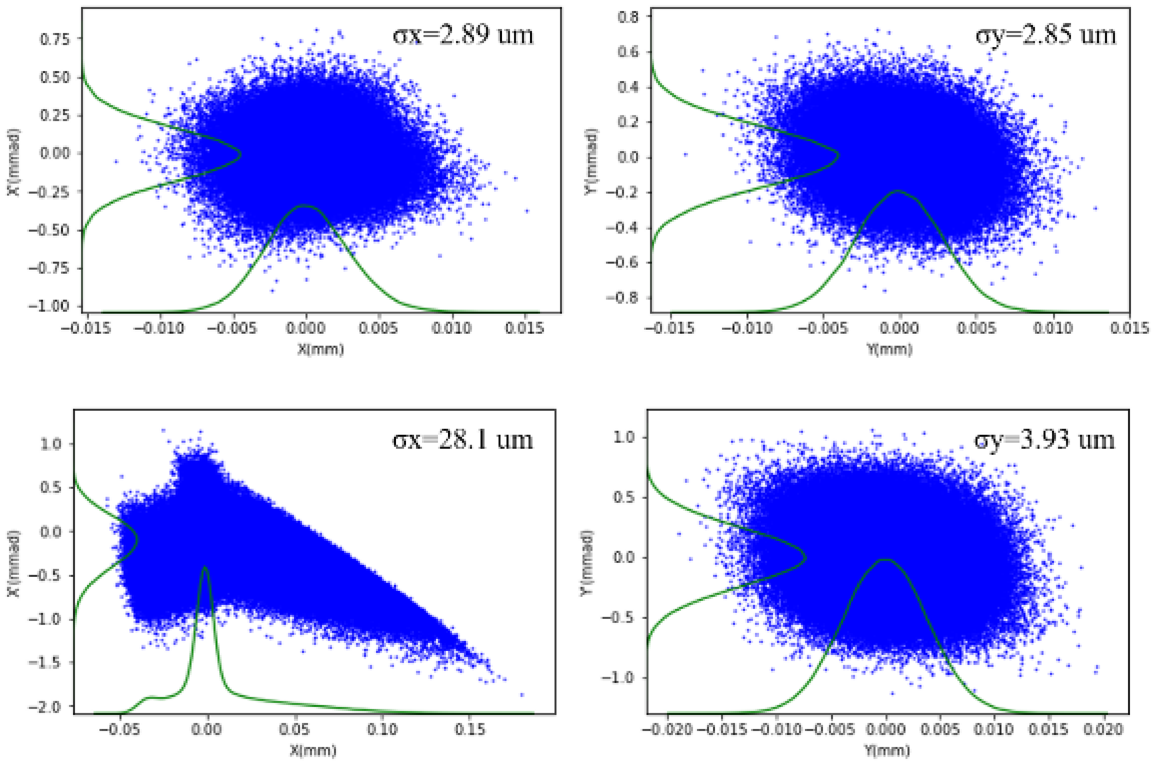


Parameter	Driver	Trailer	Total
Energy E (GeV)	11.23	10.94	11.16
Normalized emittance ϵ_n (mm-mrad) (H/V)	20.6/20.2	10.6/10.2	18.8/18.0
Bunch length (μm)	339.9	88.9	599.2
Beam size (μm) (H/V)	192/132	178/97	189/124
Charge (nC)	3.87	1.19	5.06
Energy spread	1.14%	0.34%	1.5%
Beam distance (μm)	170.4		/

Final focus optimization for CPI (by Dr. Yiwei Wang)

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	



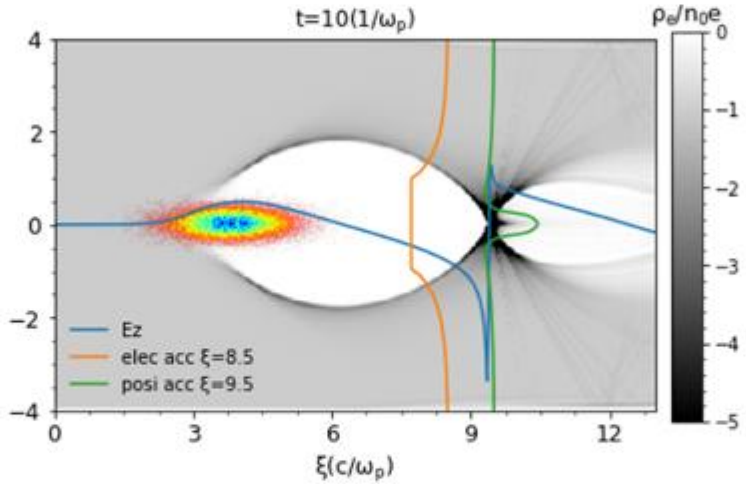


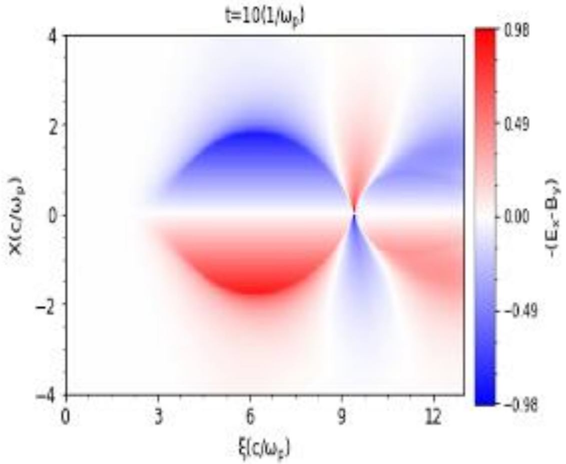
Driver's transverse emittance need further optimization. Plasma matching section as in e+ PWFA can be helpful

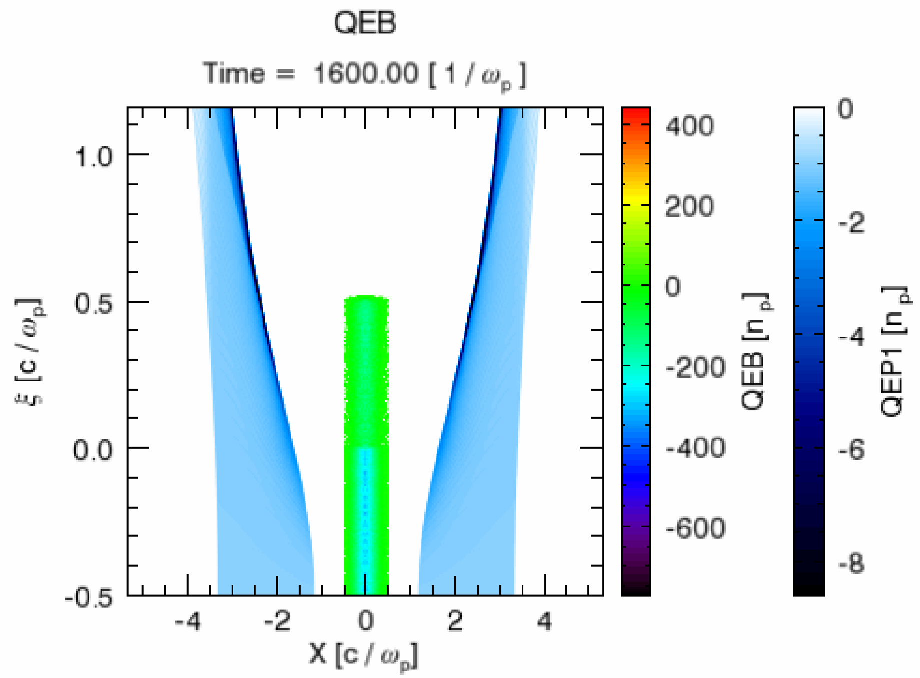
e+ PWFA for CPI (by Dr. Shiyu Zhou)

A "perfect" wakefield means:

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



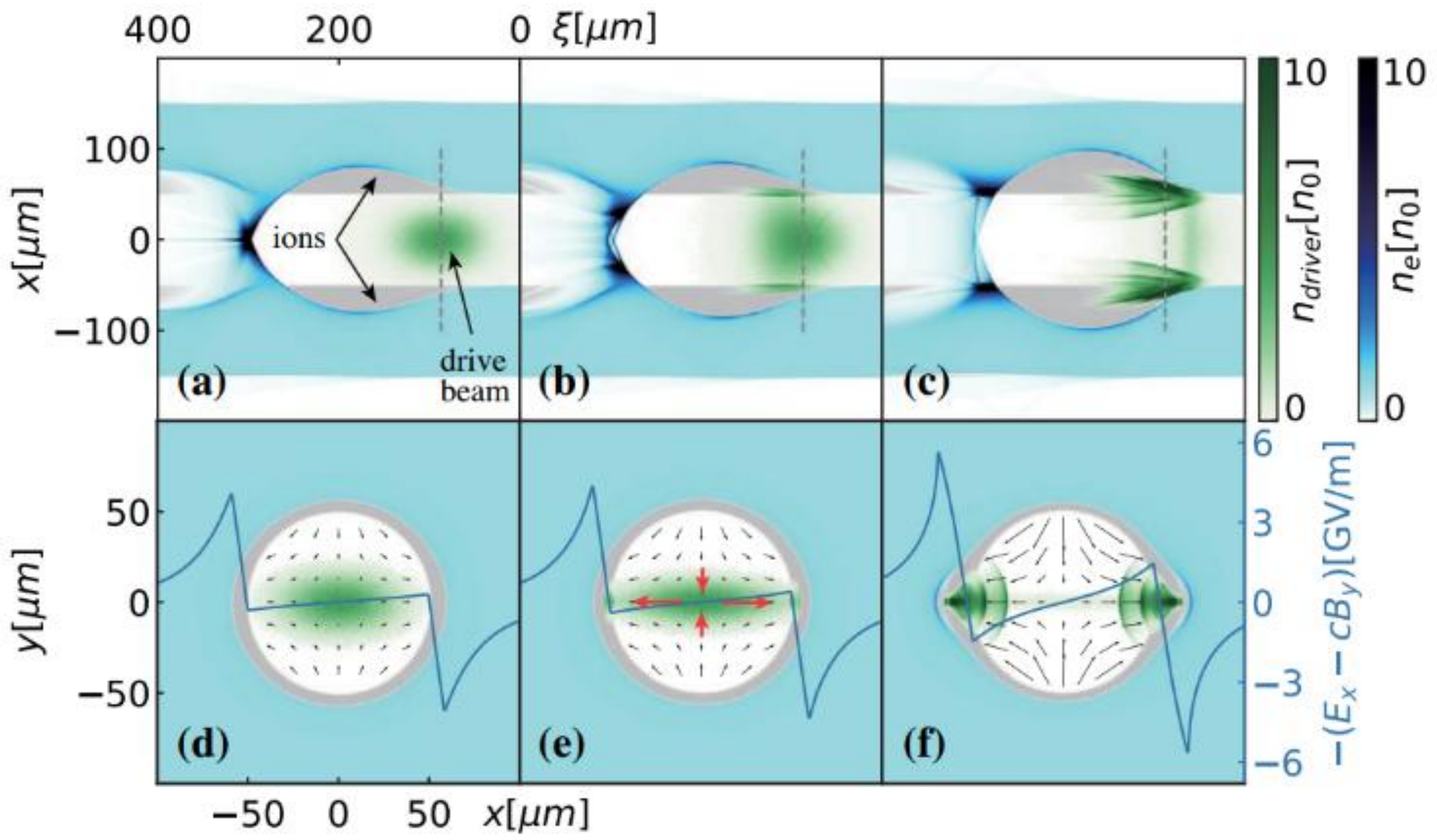


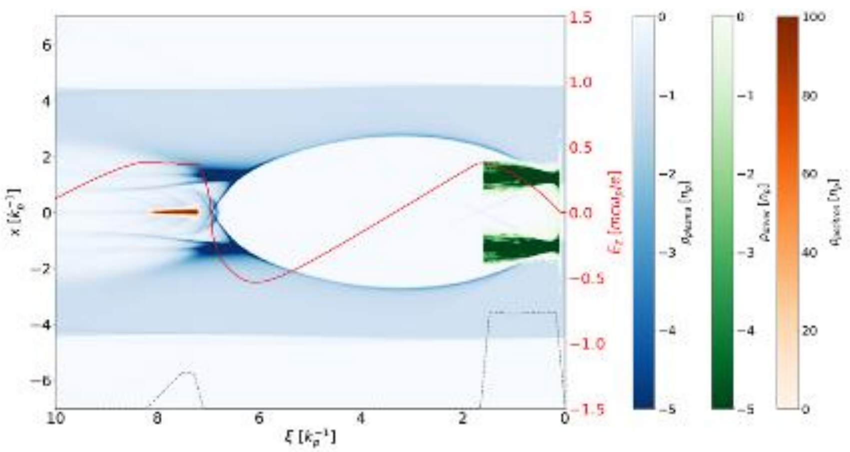


So, the blowout wakefield in uniform plasmas is quite fit for e- acceleration, while unfit for e+ acceleration

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

e+ PWFA in TDR: asymmetric beam in hollow channel





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.

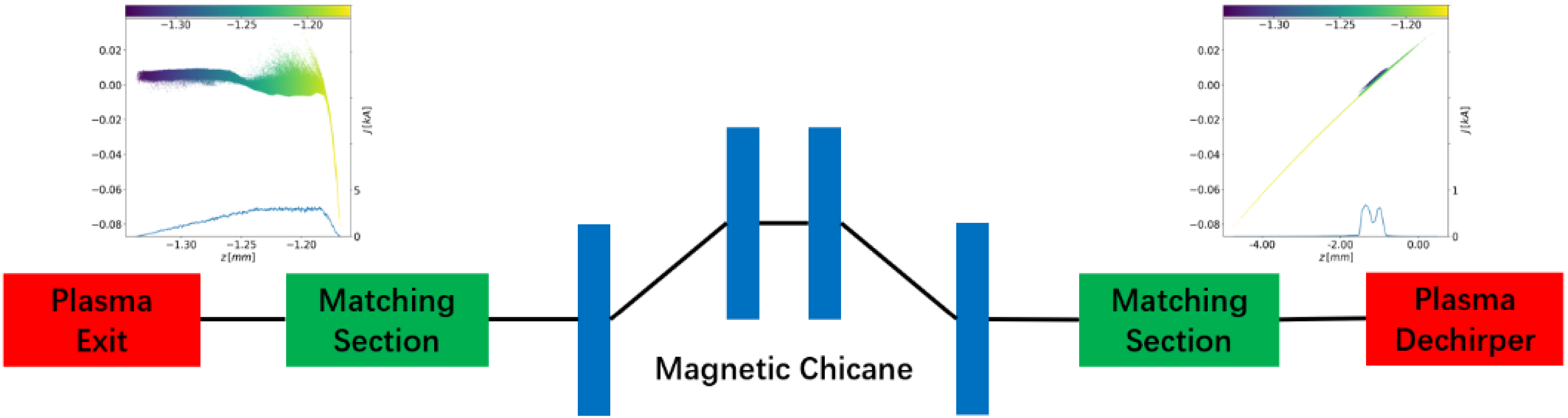
DOI: 10.1103/PhysRevLett.127.174801

e+ PWFA in TDR: asymmetric beam in hollow channel

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

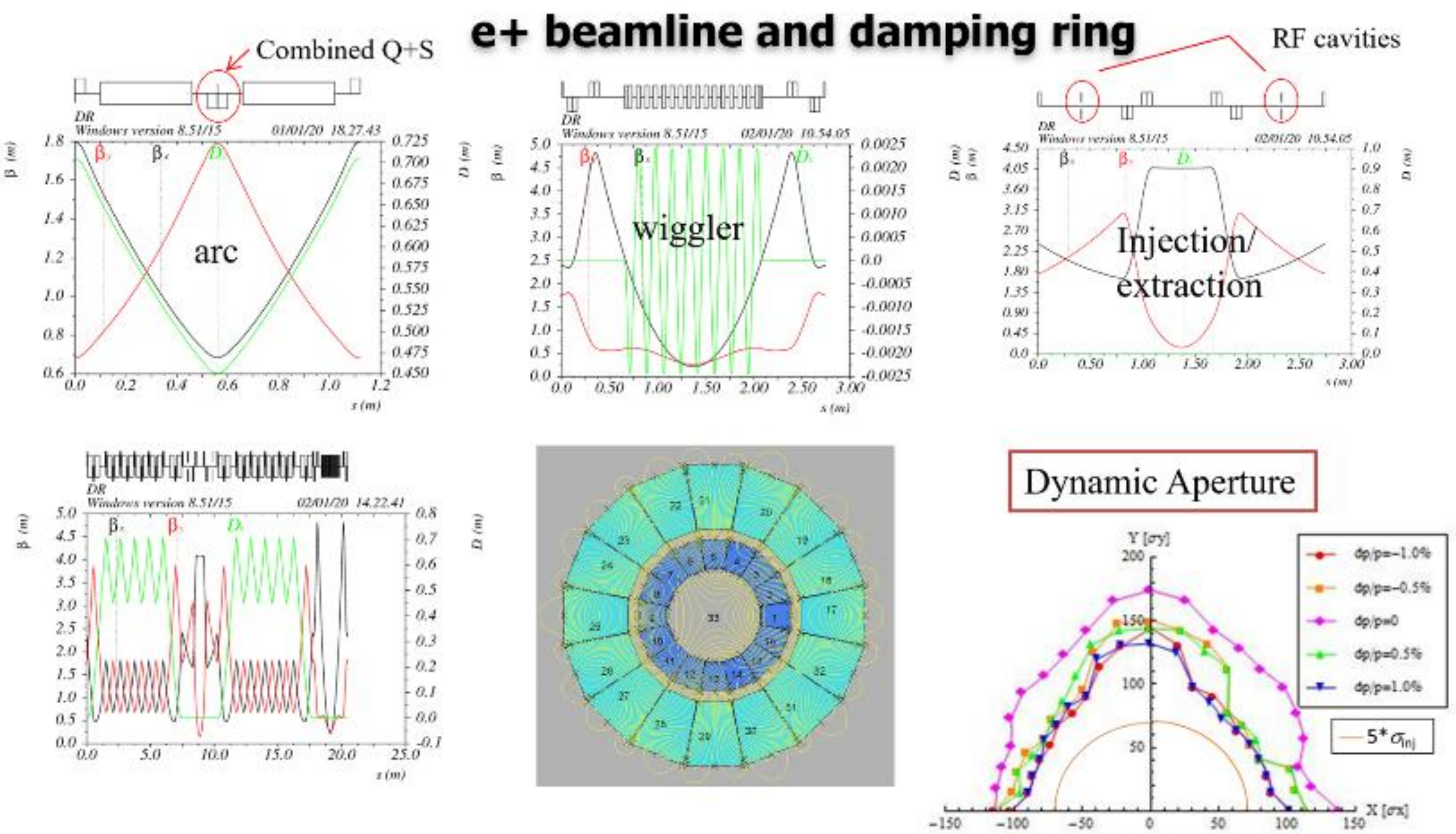
e+ PWFA in TDR: energy compression



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)

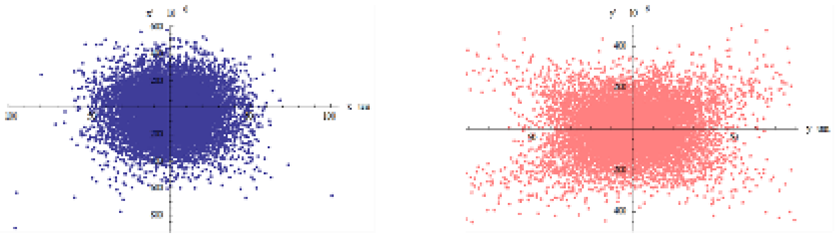
e+ beamline and DR design for CPI (by Dr. Dou Wang)



$\nu_x / \nu_y = 3.16/3.21$

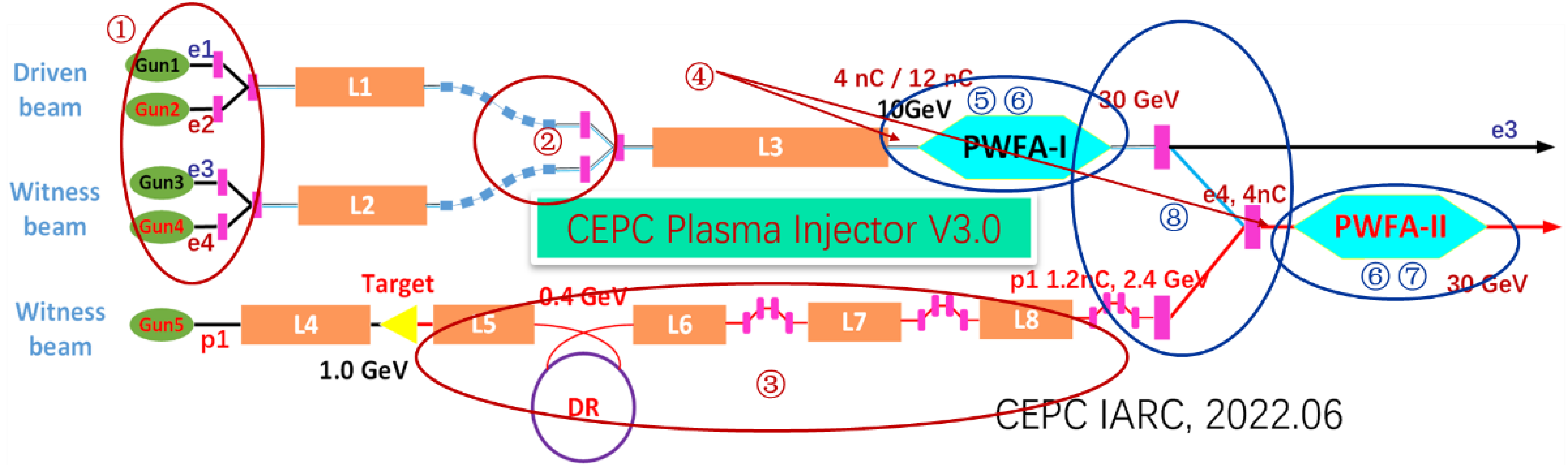
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

	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)

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

Key issues studies of CPI ---- need a dedicated TF!!

Key issues		Preliminary study/ Conceptual design	Detailed and convincing simulations / designs	Experiment test / Prototype
e- PWFA	HTR	√	√	×
	Beam quality preservation	√	√	×
	Error analysis	√	×	×
e+ PWFA	High quality practical scheme	√	√	×
	More schemes, HTR etc.	√	×	×
	High efficiency	√	×	×
Conv. acc. physics and techniques	High charge L-band RF Gun	√	×	×
	Beam profile preservation	√	×	×
	Beam merging	√	×	×
	Instrumentation	√	×	×
	Timing synchronization	√	×	×
	Positron beamline	√	√	×
Plasms source and beam manipulation	Plasma dechirper	√	√	√
	Plasma lens	×	×	×
	Plasma sources	√	√	×
	Staging	√	×	×

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CAS program on PWFA (90M RMB, 2023.10-2028.09)

中　国　科　学　院

科发函字〔2024〕99 号

中国科学院关于基础与交叉前沿科研先导专项
“束流驱动新加速原理与应用研究”
立项的通知

中国科学院高能物理研究所：

经 2023 年第 8 次院长办公会议审议通过，院基础与交叉前沿科研先导专项“束流驱动新加速原理与应用研究”正式立项。现将有关事项通知如下。

一、专项名称和依托单位

专项名称为“束流驱动新加速原理与应用研究”，依托单位为中国科学院高能物理研究所。

二、首席科学家

专项首席科学家为中国科学院高能物理研究所鲁巍研究员。

三、专项实施周期和经费概算

专项实施周期为 2023 年 10 月至 2028 年 9 月。经费概算共 9000 万元，全部由院财政支持。

四、相关要求

你单位要认真贯彻落实《中国科学院战略性先导科技专项管理办法》及其实施细则，全面履行依托单位法人责任，认真履行任务书合同条款，建立健全内部管理制度，做好专项组织实施和支撑保障工作。在专项实施过程中，要切实发挥首席科学家作用，加强专项各任务的衔接与协调；既要注重“导出”国家重大科技任务，也要进一步加强与重点实验室体系重组、人才队伍培养等重要改革举措的衔接，注重形成合力，推动科研布局调整优化，促进出成果、出人才；要立足专项特点，建立健全有利于领军人才和青年人才成长的举措和机制，激发创新人才活力；要做好资金管理使用工作，确保资金专款专用，提高资金使用效益；要加强知识产权和成果管理，履行科研诚信建设主体责任，强化专项科研绩效管理，确保专项按期高质量实现预期目标。

附件：基础与交叉前沿科研先导专项“束流驱动新加速原理与应用研究”专项（项目）清单

中国科学院

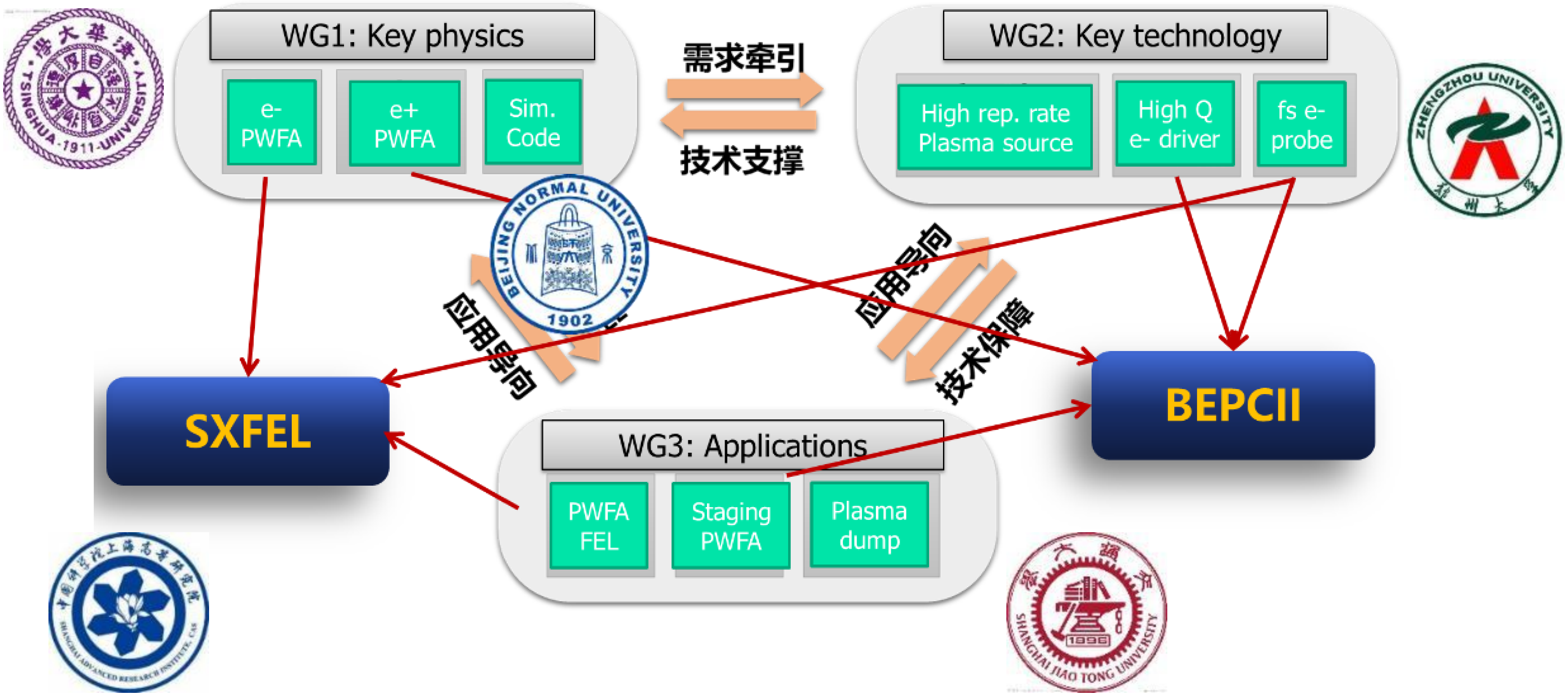
2024 年 2 月 2[illegible] 日

（此件依申请公开）

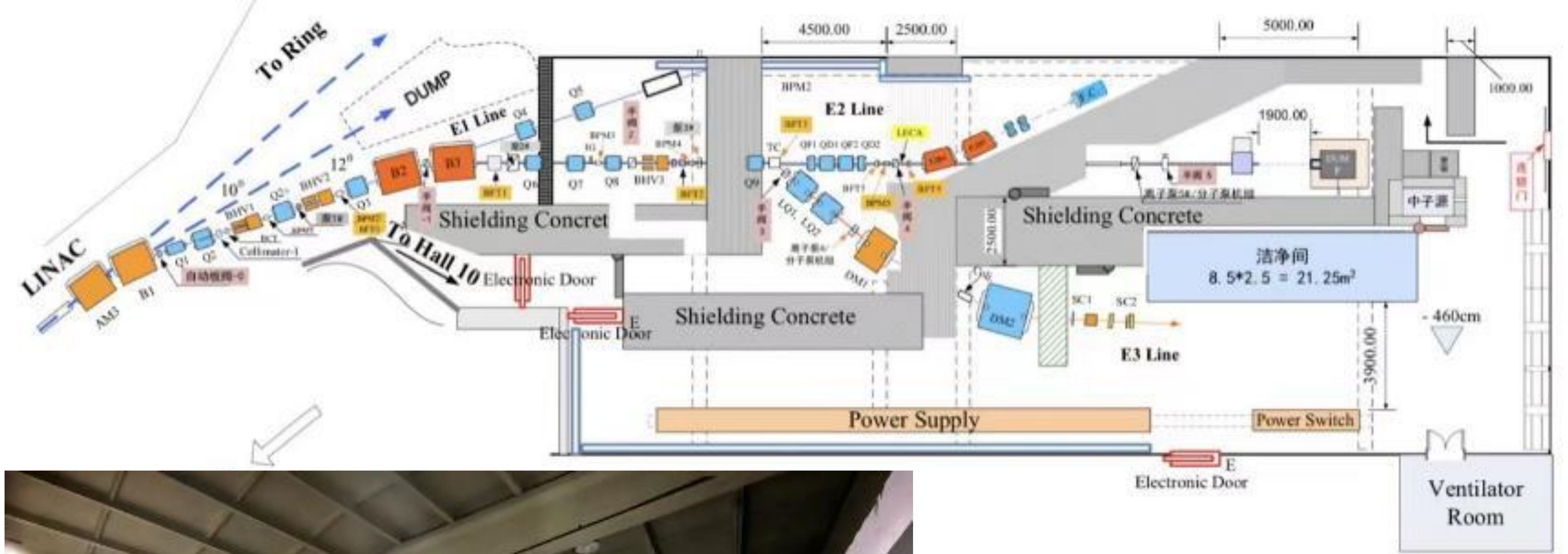
抄送：办公厅、前沿科学与基础研究局（筹）、财务与资产管理局（筹）、人事人才局（筹）、科技基础能力局（筹）、监督审计局。

— 2 —

CAS program on PWFA: 3 projects, 9 topics, 5 colleagues

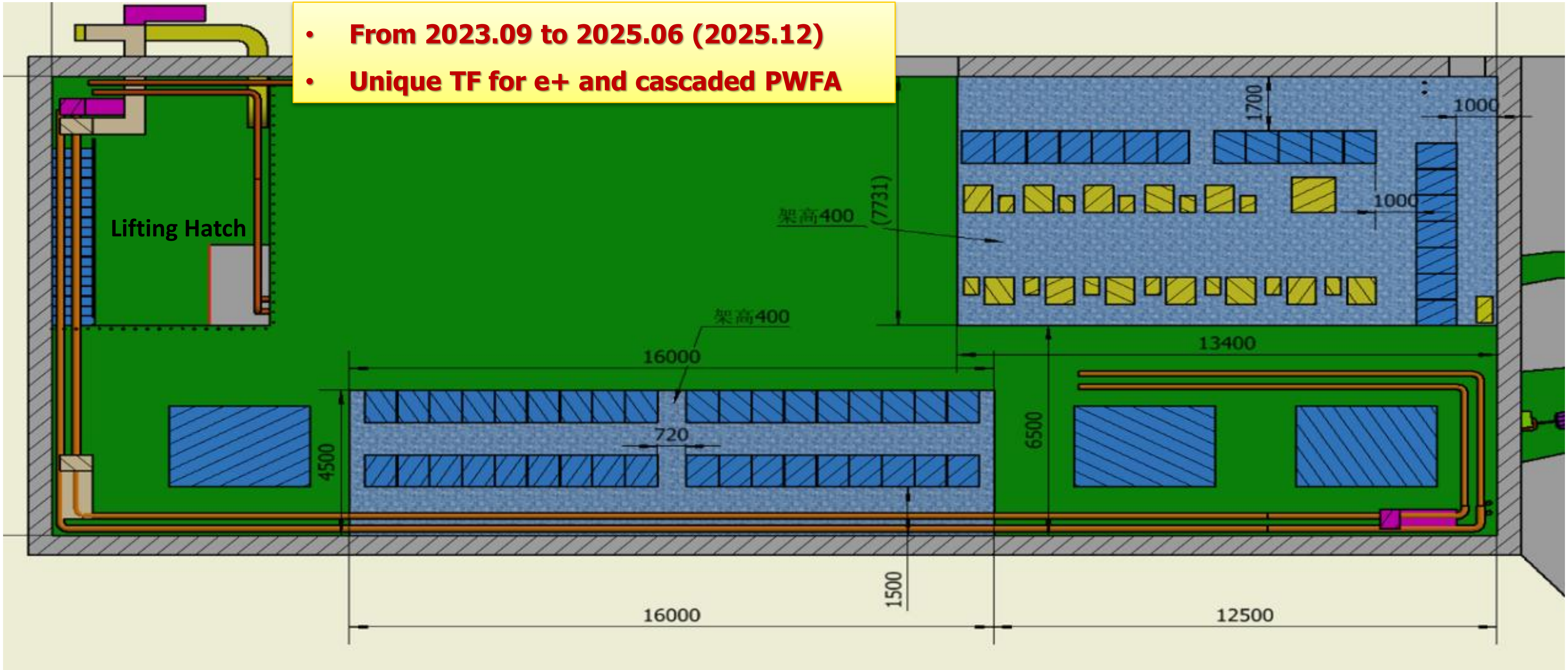


Hall 10 @ IHEP was used for detector calibration



PBA TF proposal based on BEPCII linac

- **From 2023.09 to 2025.06 (2025.12)**
- **Unique TF for e+ and cascaded PWFA**



PBA TF progress ---- clear the lab (2023.11-2024.03)






PBA TF progress ---- re-construction (2024.05-2024.09)





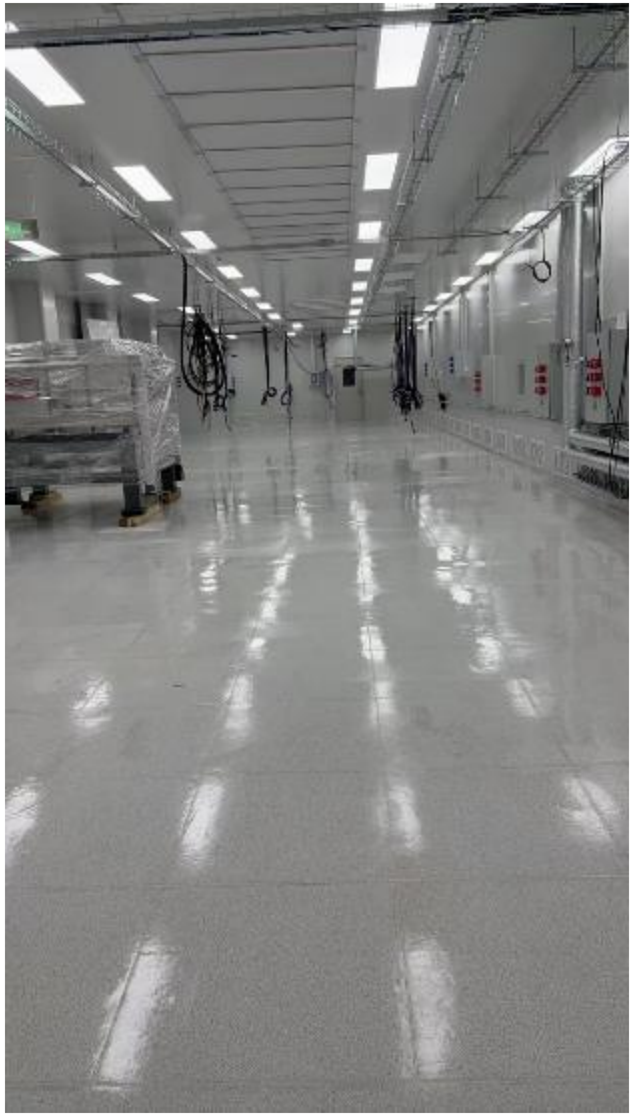

PBA TF progress ---- utility renovation (2024.10-2025.10)

PBA TF progress ---- replace the double girder crane

PBA TF progress ---- clean room and cooling water system

PBA TF progress ---- beamline installation in B2 tunnel

PBA TF progress ---- Current Status



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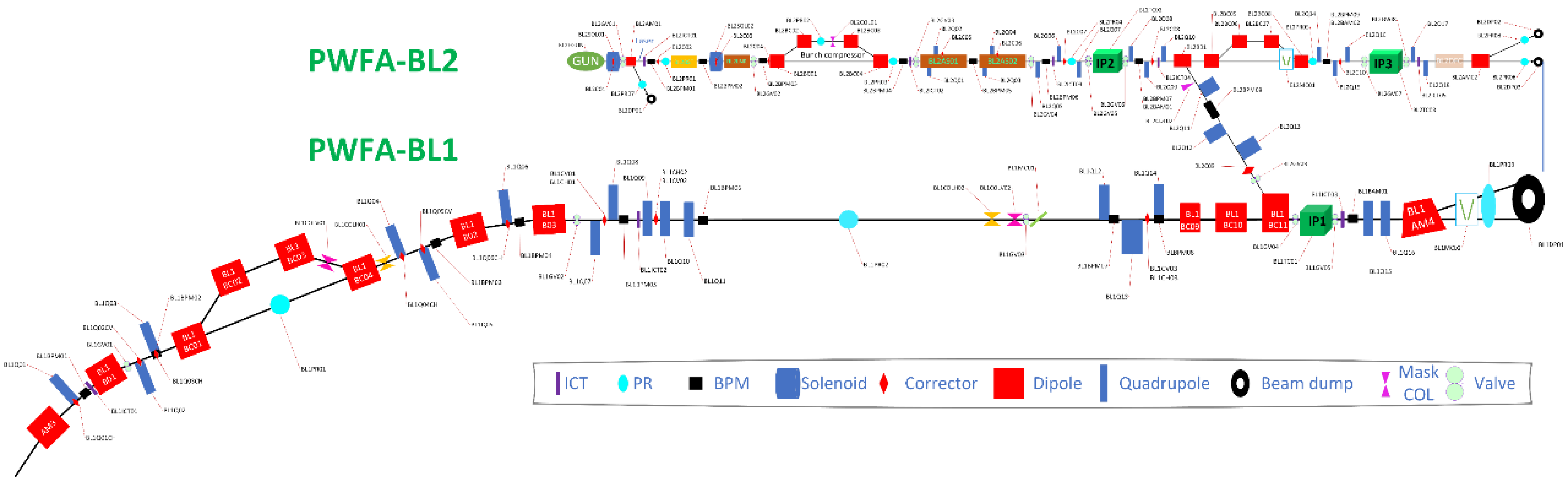
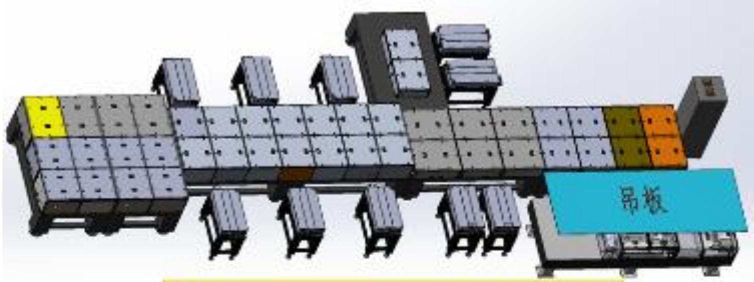
TF Beamlines design (by Y. W. Wang, C. Meng, H. S. Xu…)

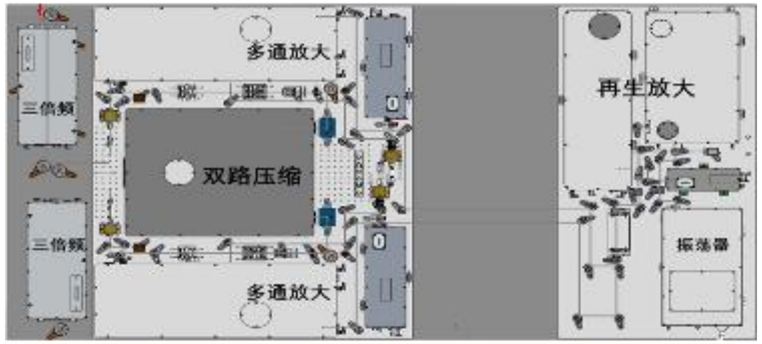


Parameters	Unit	BL-I e- (AM3)	BL-I e- (IP1)	BL-I e+ (AM3)	BL-I e+ (IP1)	BL-I e- (IP1, block)	BL-I e+ (IP1, block)	BL-II e- (IP2)	BL-II e- (IP1)
Energy	GeV	2	2	2	2	2	2	0.15	0.15
Charge	pC	2000	2000	100	100	9.4	0.2	5000	1000
bunch length	ps	10	1	10	1	~1	~1	0.7	1
Geo. emittance	mm·mrad	0.1/0.1	0.1/0.1	0.4/0.4	0.4/0.4	0.011/0.005	0.04/0.02		
RMS beam size	µm	-	150/150	-	300/300	30/40	54/76	35/22	100/50

Light path design of PW laser and RF gun drive laser

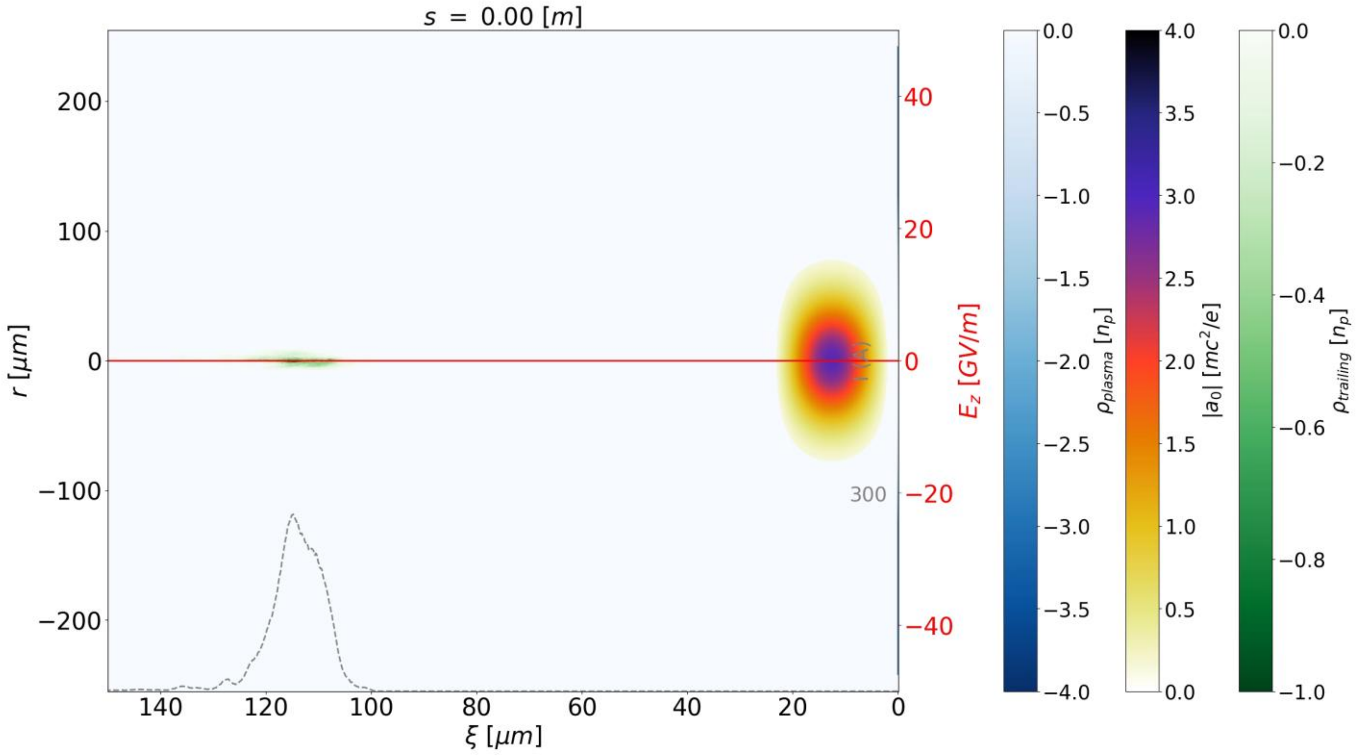


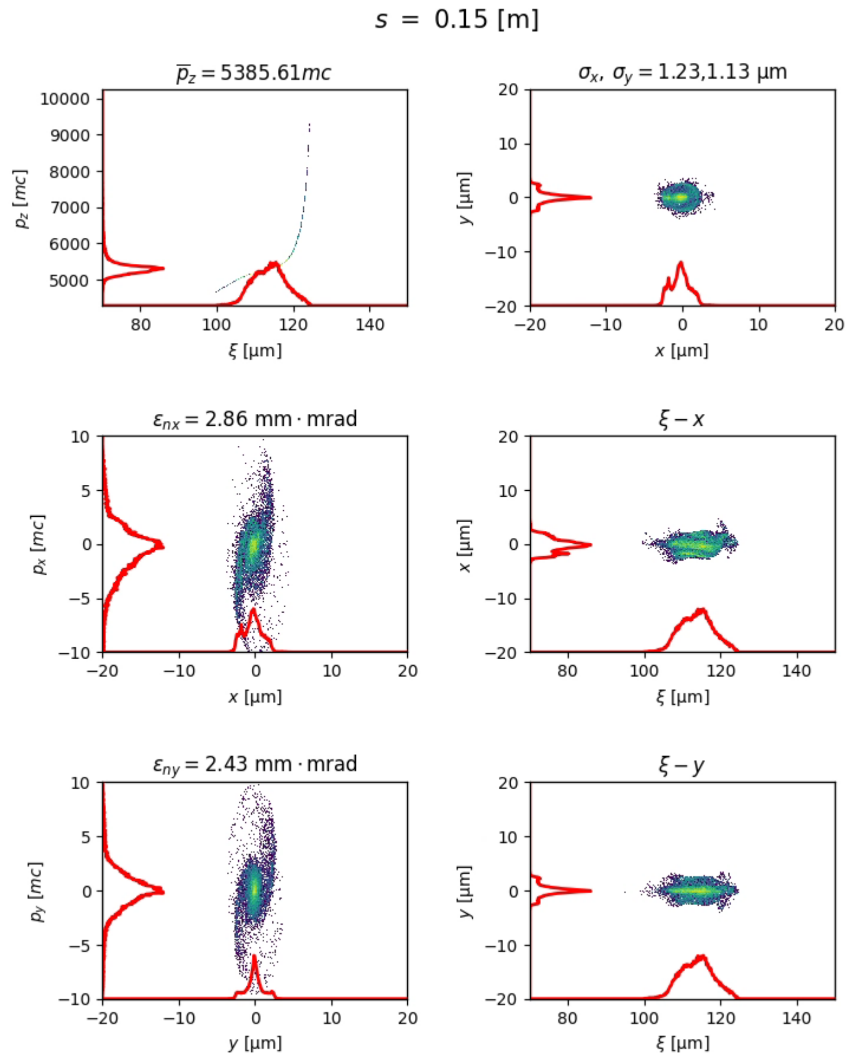
PW laser system



drive laser of L-band e- gun (4 m × 1.5 m)

PBA experiment proposals —— LWFA e- external injection

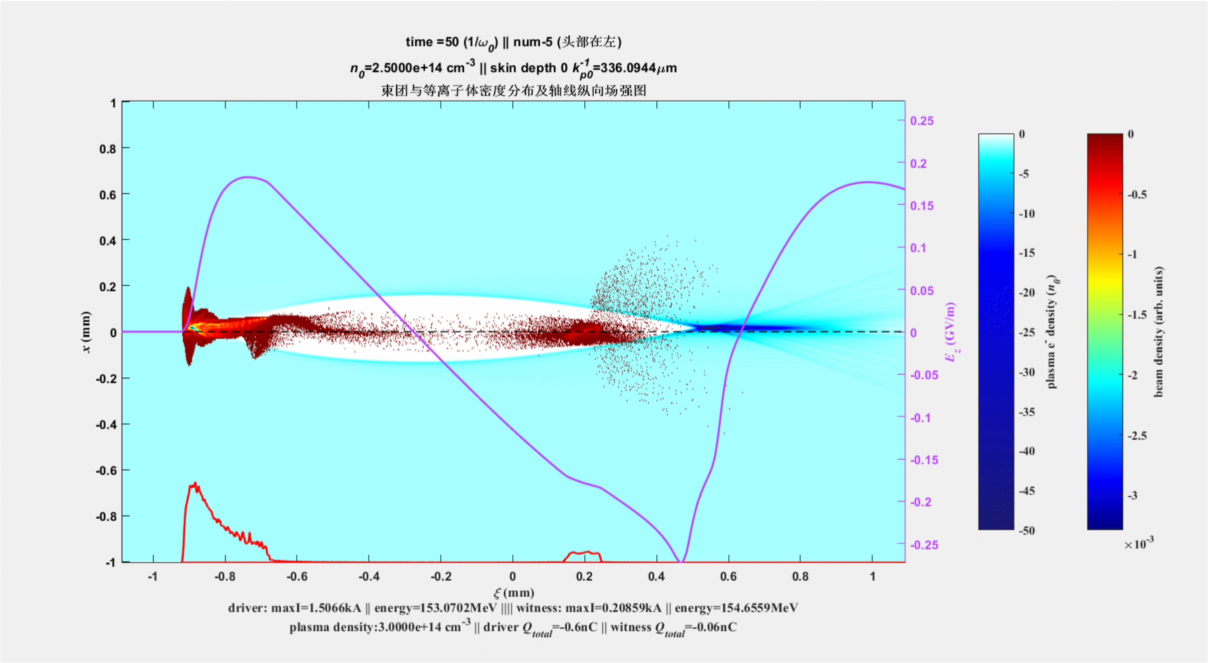


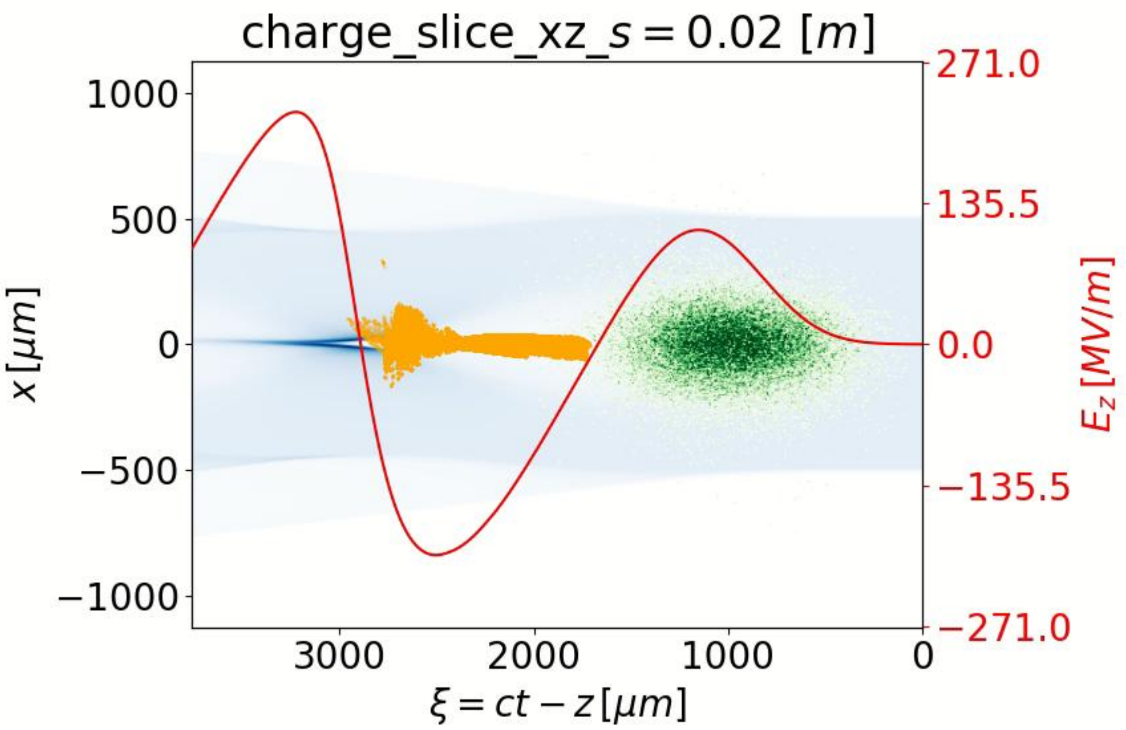


PW Laser + BL2 e- (9.45 pC)

E~16.6 GeV， rms energy spread ~ 7.7%

PBA experiment proposals —— cascaded acceleration





Stage 1: PWFA @ IP2

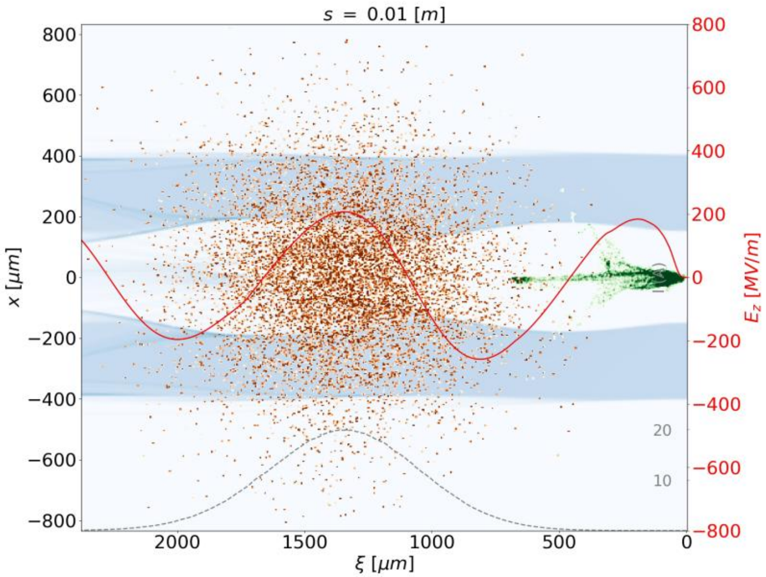
L-band e- gun generate 2 bunches
Trailer is accelerated from 150 MeV to 170MeV

Stage 2: PWFA @ IP1

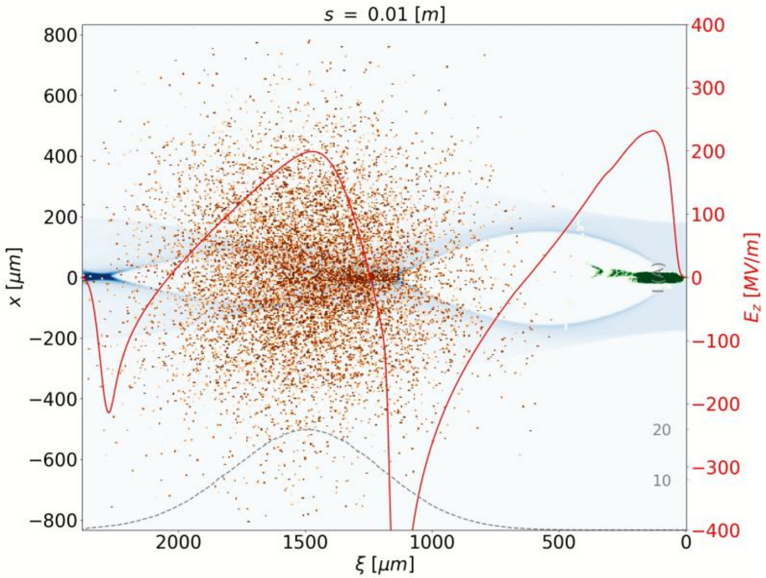
Use 2 GeV e- bunch from BEPCII linac as driver
Trailer is accelerated from 170 MeV to 310 MeV

PBA experiment proposals —— PWFA e+ acceleration

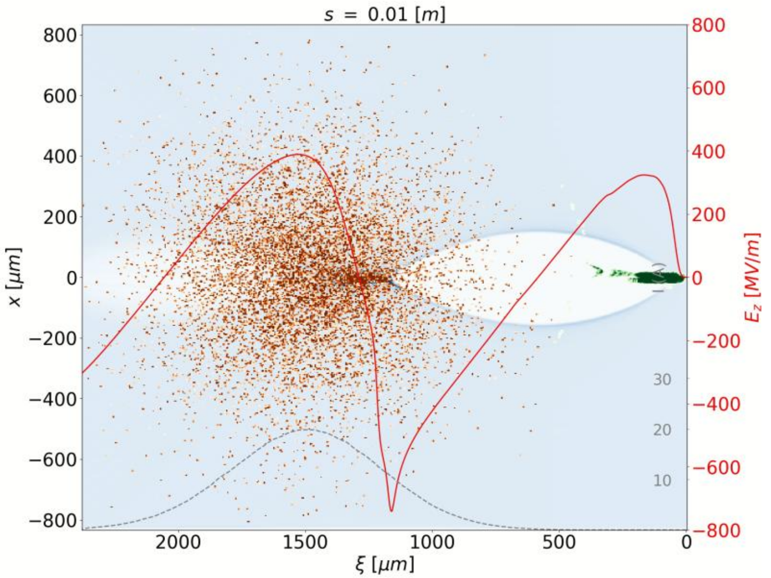
hollow channel plasma



finite-width channel



uniform plasma

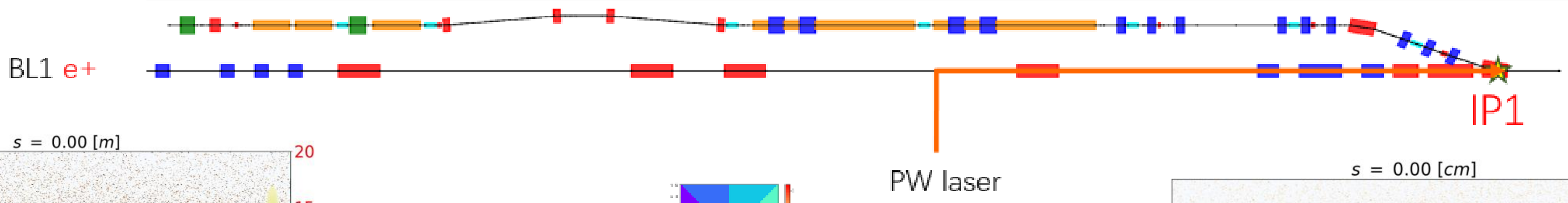


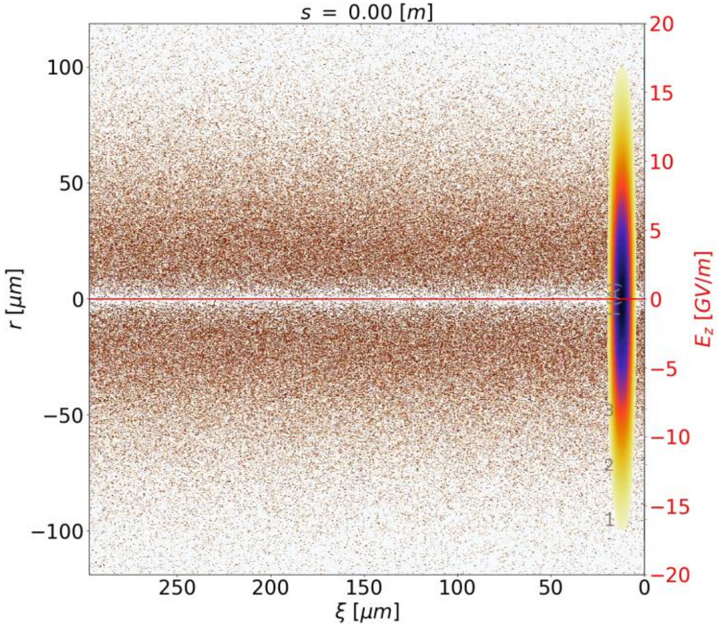
Use BL2 e- as driver, and e+ from BL1 as trailer

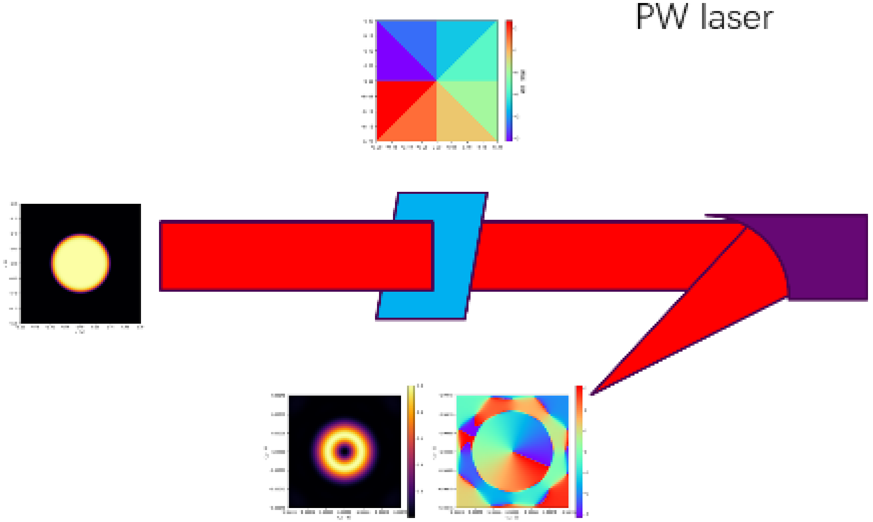
Try different schemes for better capture efficiency and beam quality

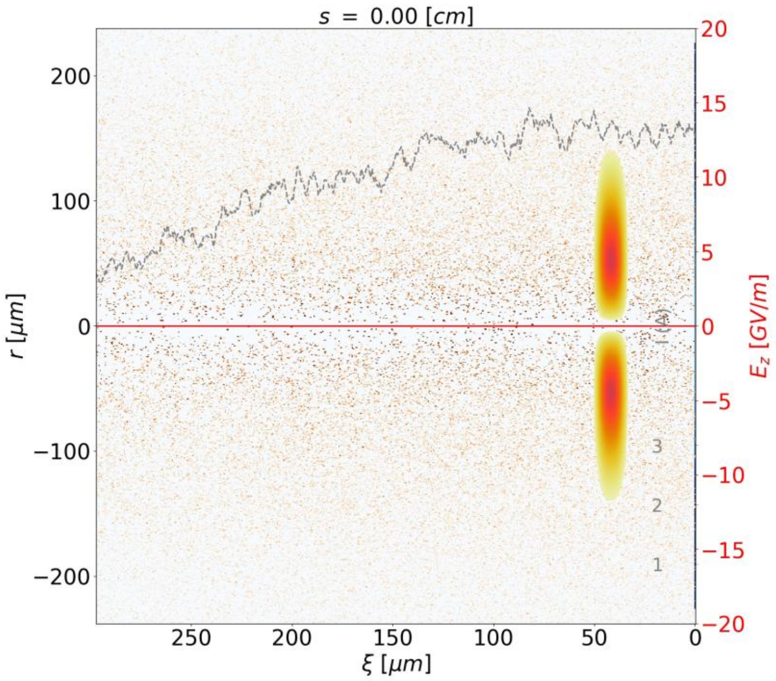
PBA experiment proposals —— LWFA e+ external injection

- PW laser + BL1 e+









Laser: 18J, a0=2.4, w0=60um, τ=25fs

e+: 50pC, 2GeV, $\sigma_r = 40um$, σ_z ~ 1ps

Plasma: ~ 1e17cm-3

Both e+ energy gain > 1GeV

Laser: 19J, a0=1.1, w0=75 um, τ=30fs

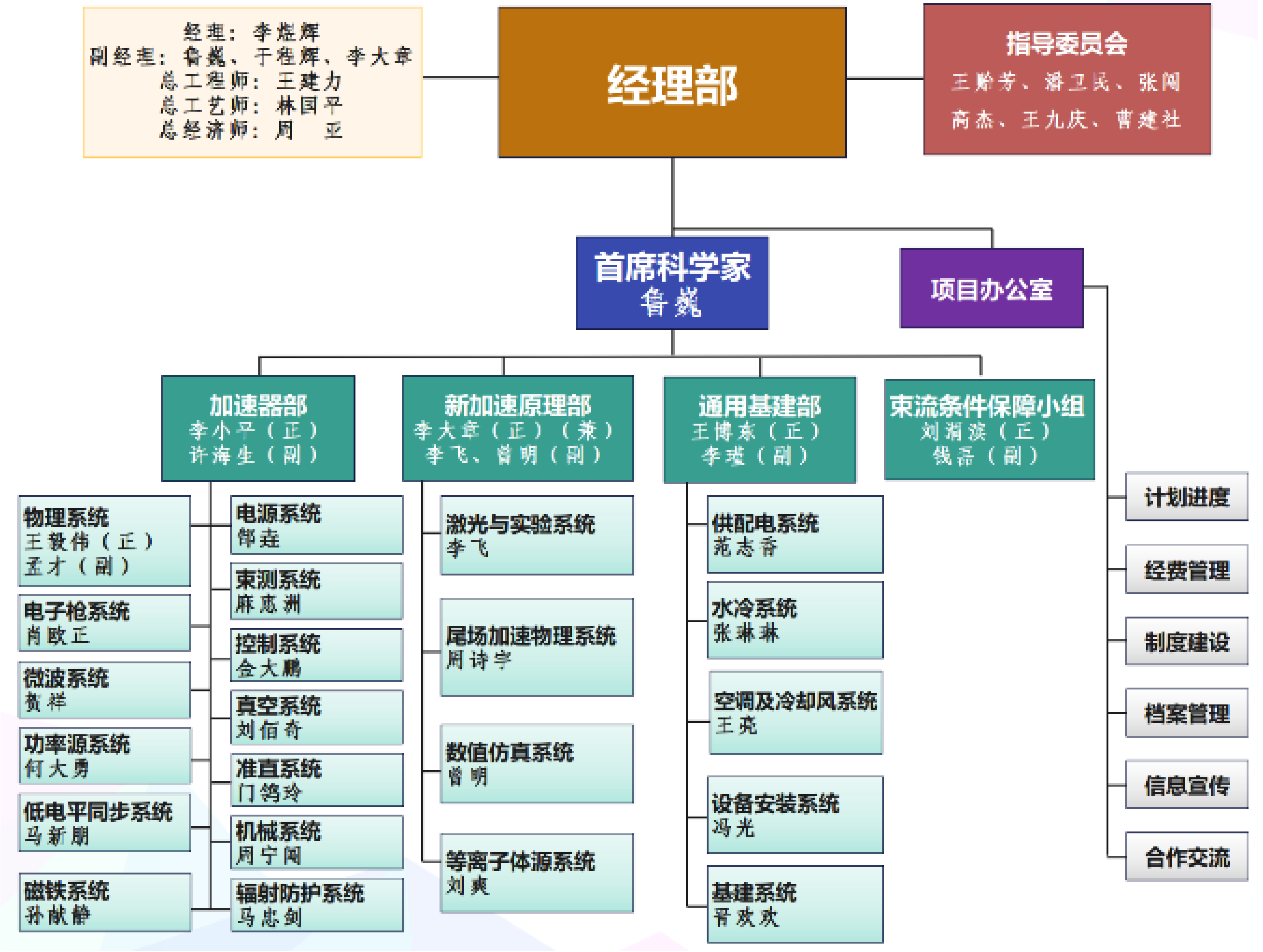
e+: 7.5 pC, 2GeV, $\sigma_r = 40um$, σ_z ~ 1ps

Plasma: ~ 5e16+2e16×(r(μm)/75)2

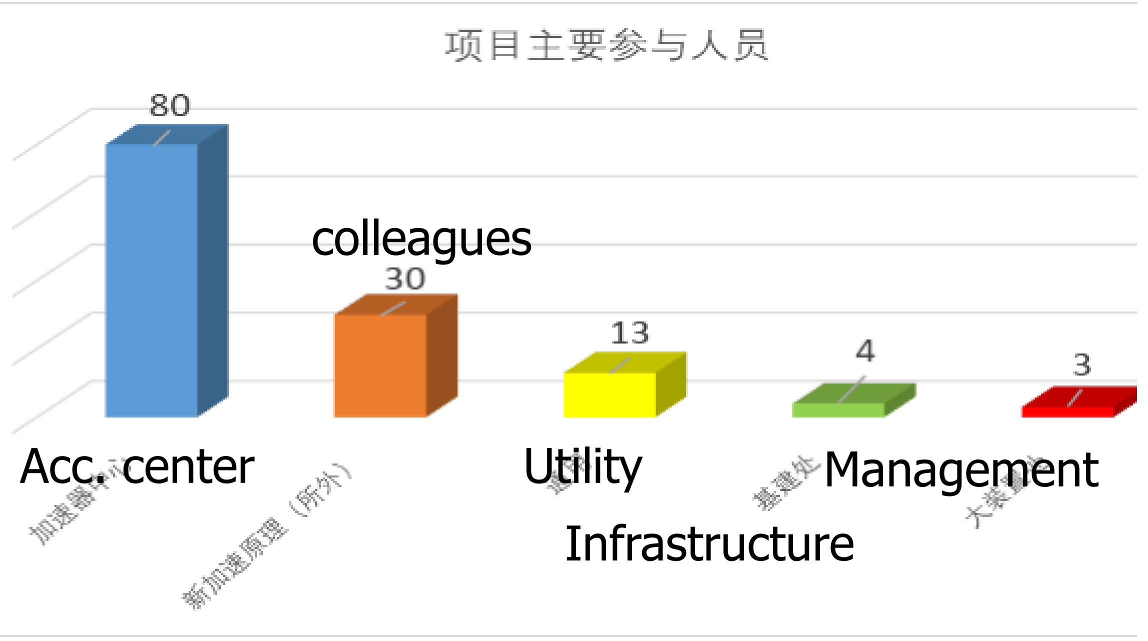
Outlines

- Motivation
- CEPC Plasma Injector
- PBA TF based on BEPCII linac
- **Summaries and prospects**

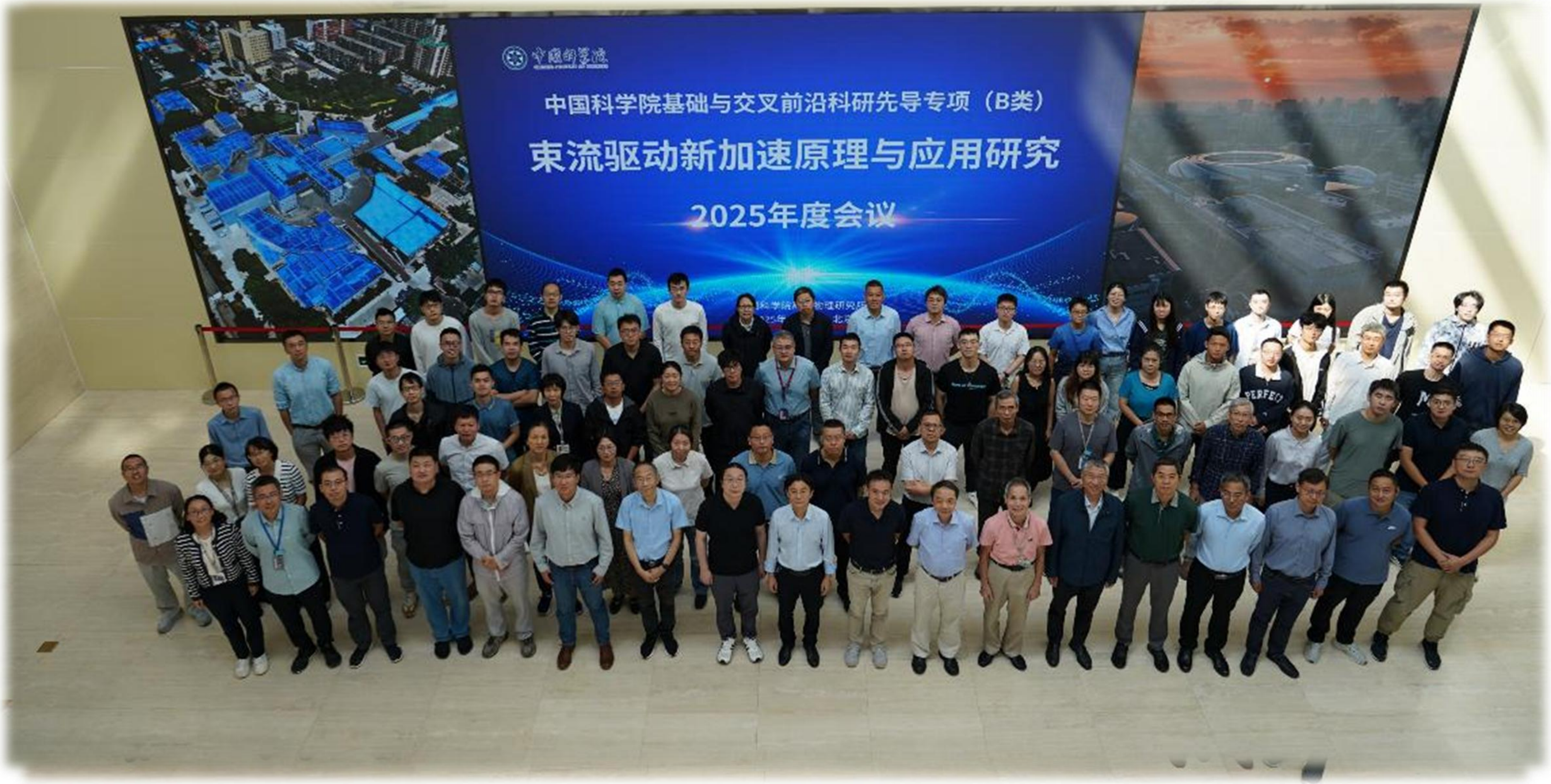
Organization and Manpower of IHEP PBA study



- Manpower: ~130（100+ @ IHEP）；
- Weekly meeting: 59 (2023.10.9-2025.01.13)

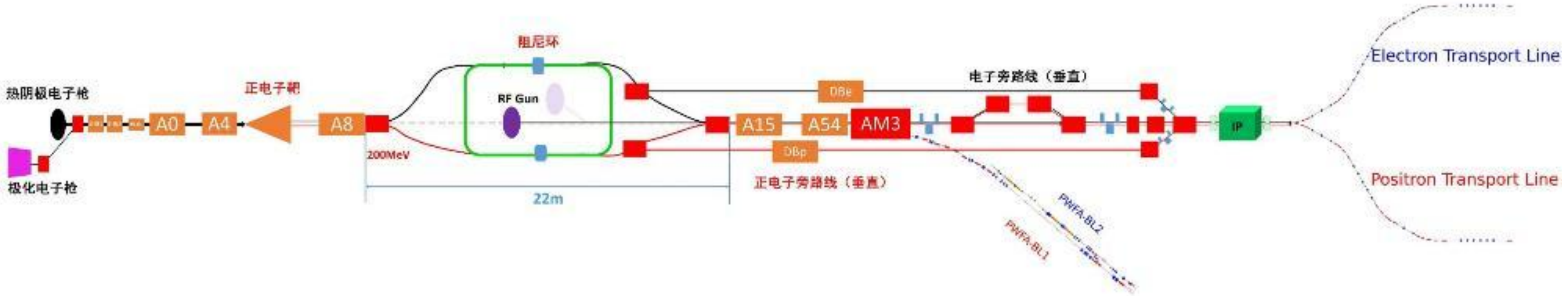


Group photos at project annual meeting (2024 & 2025)



Summaries and prospects

- **Focused on PWFA TF construction in the last 2 years**
  - ✓ BL1 will be ready this month, and BL2 is expected to be ready early next year
  - ✓ Beam commission preparation and experiment proposal optimization are ongoing
- **The delay of CEPC will not diminish the importance of the TF**
  - ✓ It's NOT only for plasma acceleration, but also for conventional accelerator R&D
  - ✓ It's NOT only for CPI, but also for a real plasma accelerator, or even plasma collider
- **B2 beam quality (especially e+ quality) and lab space limits the TF performance**
  - ✓ Another upgrade after B2U is under consideration (a mini DR will be installed in B2 linac tunnel)



Thank you and welcome to IHEP