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

CEPC Plasma Injector Status and Test Facility Plan

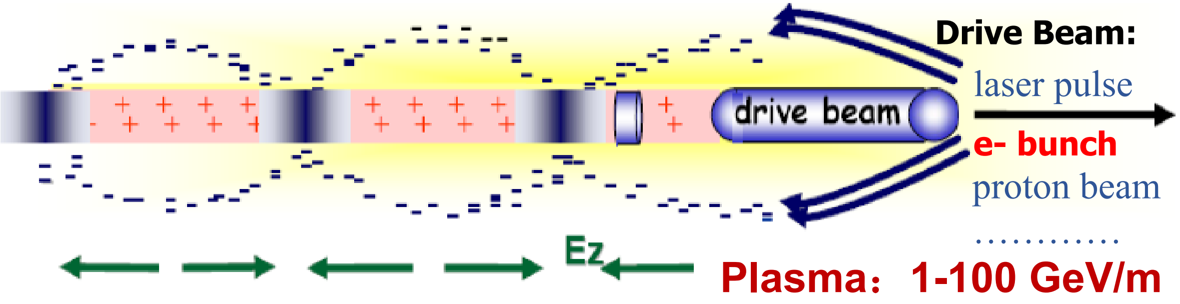
Prof. Wei Lu, Dr. Dazhang Li, et al.

On behalf of the IHEP-THU-BNU AARG team

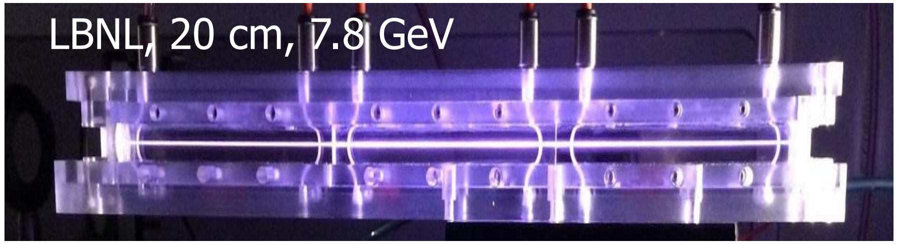
Outlines

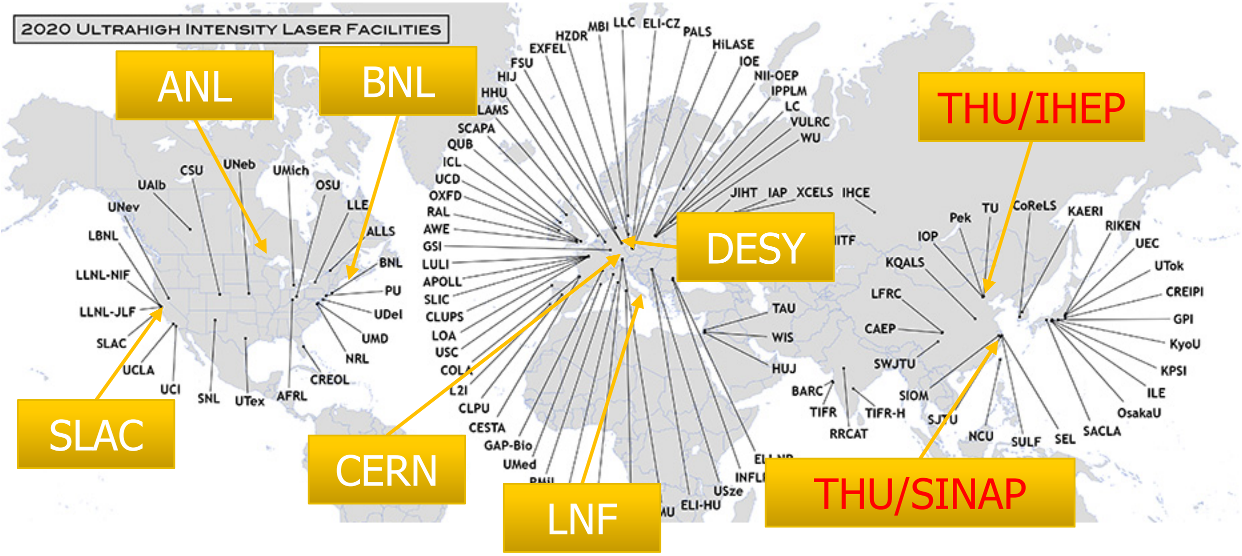
- **Introduction to CEPC & CPI**
- **Current status of CPI studies**
- **Roadmap and proposed test facilities**

Plasma acceleration: > 1000 gradient increase



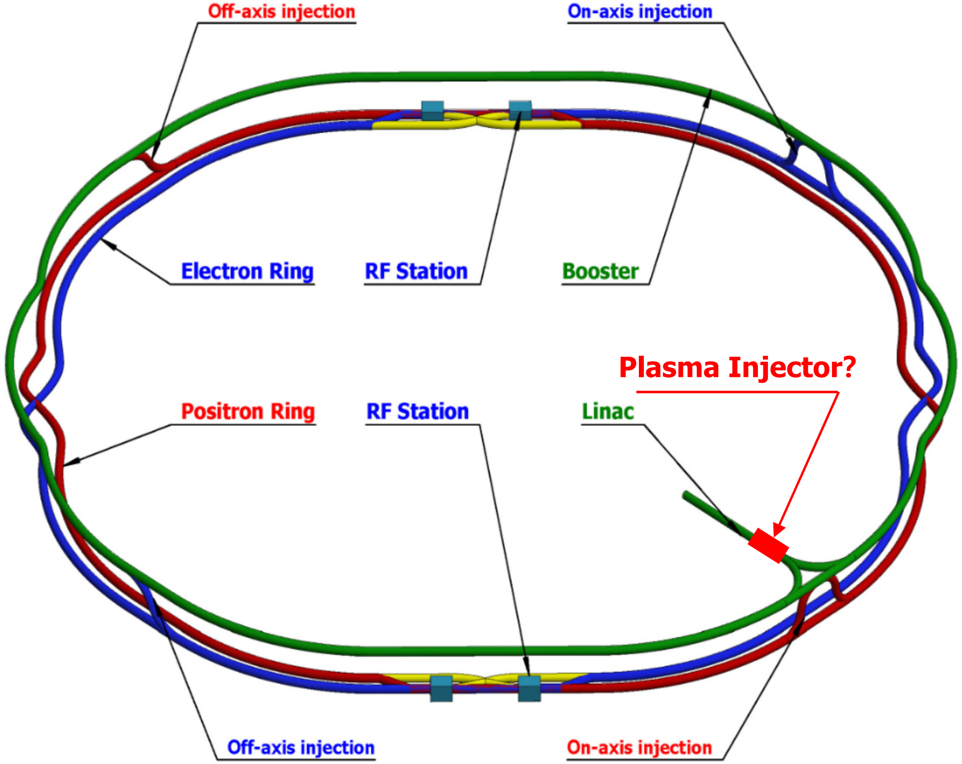
- Table-top X/γ sources
- High Energy colliders
- HEDP platforms





Affiliations/institutes on PWFA Study

100 km Booster → Low field dipole problem



Linac → 100 km Booster → e- ring / e+ ring

If the linac is only 10 GeV (as in CDR 2018)

- Min. magnetic field for a booster bending magnet = 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.

Either use the new type magnet, or increase the linac energy: ~1B RMB cost rise !!

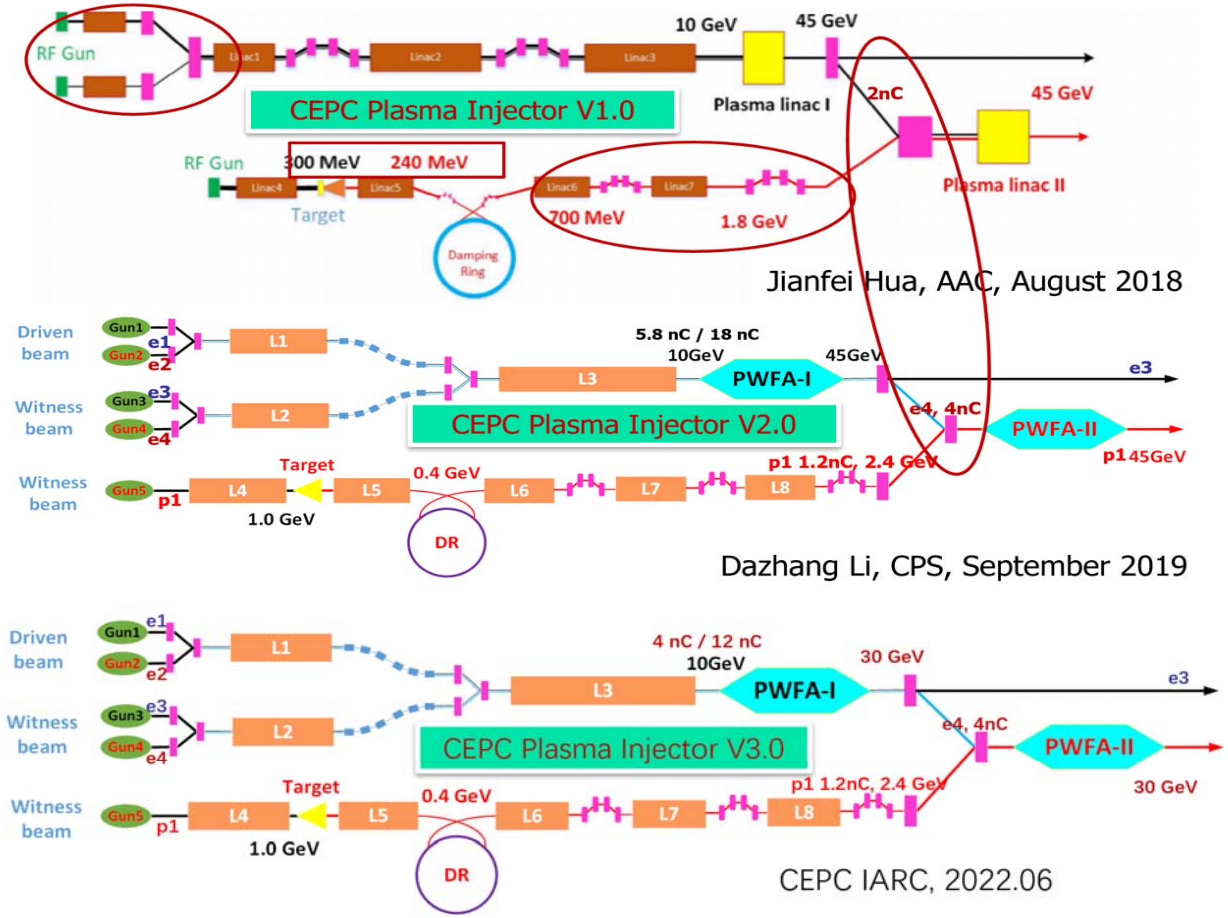
CPI: CEPC Plasma Injector, since 2017

Use a ~ 10m plasma accelerator to boost the beam energy from 10 GeV to 30 GeV, or even higher

1st collaborated group meeting on 2017. 03

1st KEY conclusion: use PWFA not LWFA!

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



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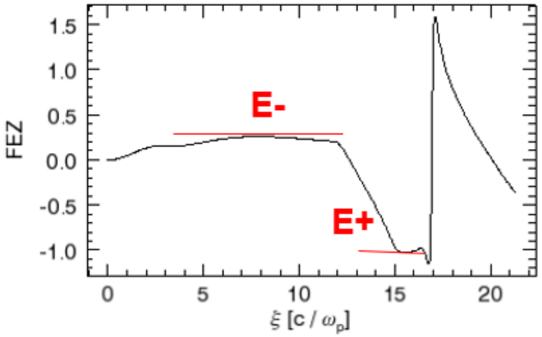
CPI e- acceleration: Transformer Ratio (TR)



$$TR = E^{+}/E^{-}$$

$$TR = \frac{\overline{\gamma}_{trailer} - \gamma_{trailer\_initial}}{\overline{\gamma}_{driver} - \gamma_{driver\_initial}}$$

$$\eta = \frac{\sum_{i=1}^{n}{}_{E_i > E_t} (E_i - E_{trailer}) q_i}{\sum_{j=1}^{n}{}_{E_d > E_j} (E_{driver} - E_j) q_j}$$

For CPI V1.0 and V2.0

TR ≥ (45.5-10)/10=3.55

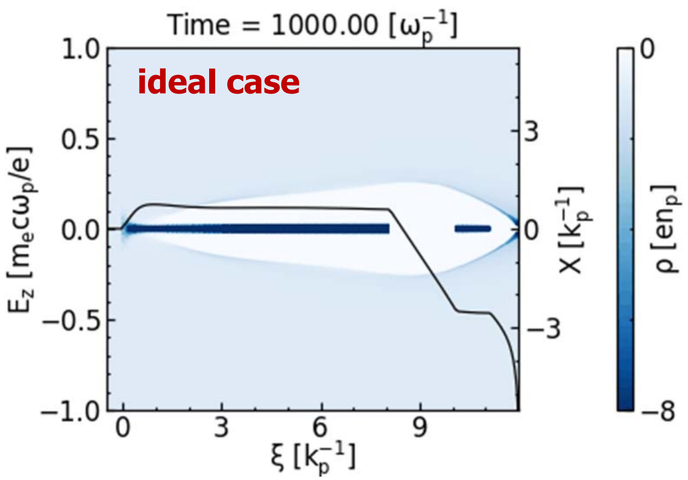
For CPI V3.0

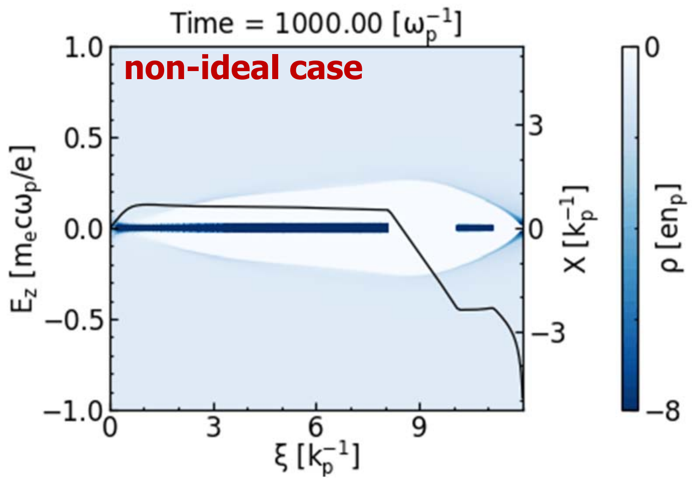
TR ≥ (30-10)/10=2

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





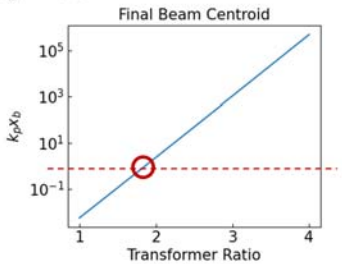
CPI e- acceleration: Transformer Ratio (TR)

- Transformer ratio R, Energy transfer efficiency 60%
- $Q_w = 1\text{nC}$, $Q_d = 1.67R\text{nC}$, Beam size σ_r
- Initial noise level $\sim \frac{\sigma_r}{\sqrt{N}} = \frac{1.27\sigma_r}{\sqrt{1+1.67R}} \times 10^{-5}$
- Drive beam length $k_p L_d \sim 2R$
- Witness beam length $k_p L_w \sim 1$
- Initial energy γ_0
- Accelerating distance $k_p s \sim \gamma_0 R$

➢ We can obtain the final beam centroid of the witness beam at the end of the acceleration

➢ $x_b \sim \frac{1.27\sigma_r}{\sqrt{1+1.67R}} \times 10^{-5} \times e^{1.3\left(\frac{\gamma_0}{2}\right)^{\frac{1}{6}} c^{\frac{1}{3}} c_b^{\frac{1}{3}} R^{\frac{1}{3}}\left(\sqrt{2}R+\frac{1}{\sqrt{2}}\right)^{\frac{2}{3}}}$

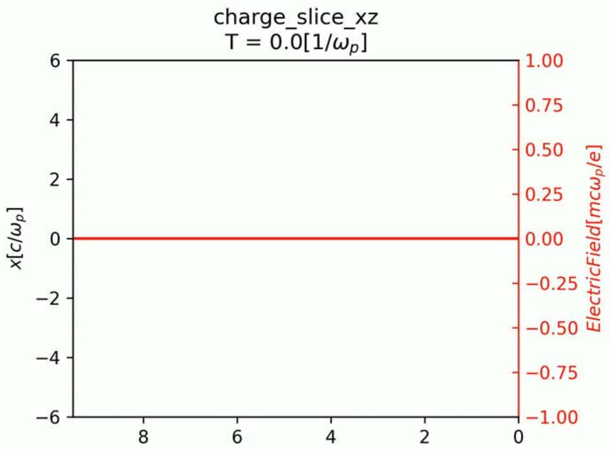
➢ For a 10GeV driver, beam size $k_p\sigma_r = 0.2$, c=0.7, $c_b = 0.8$



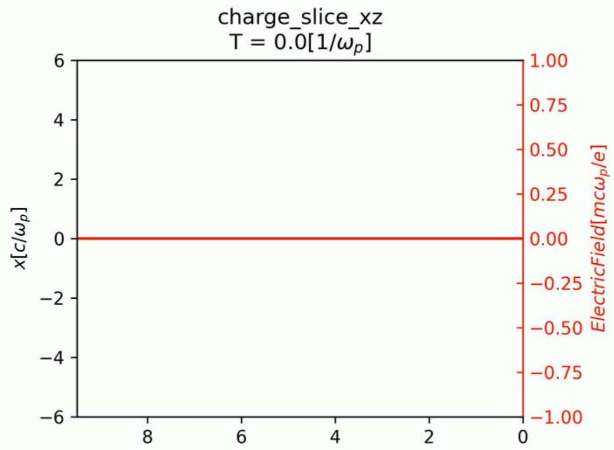
TR ≤ 1.8 seems acceptable ($x_b < 1$) if no extra damping mechanism is adopted.

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

Ion motion can significantly decrease the hosing instability



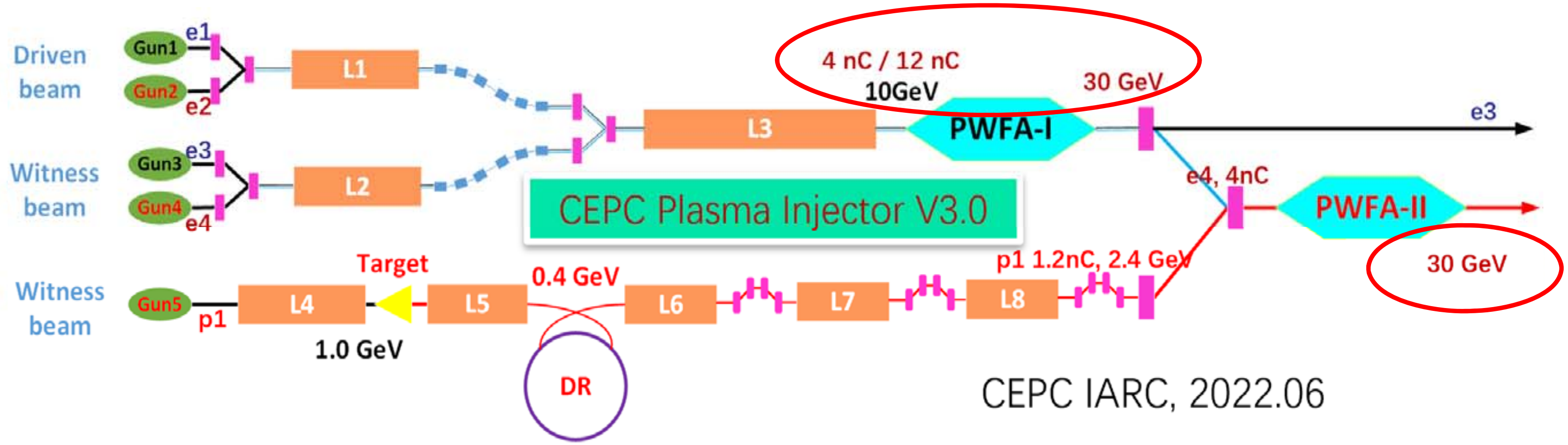
TR=2 without ion motion

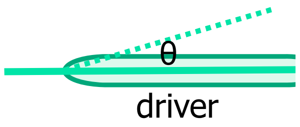


TR=2 with ion motion

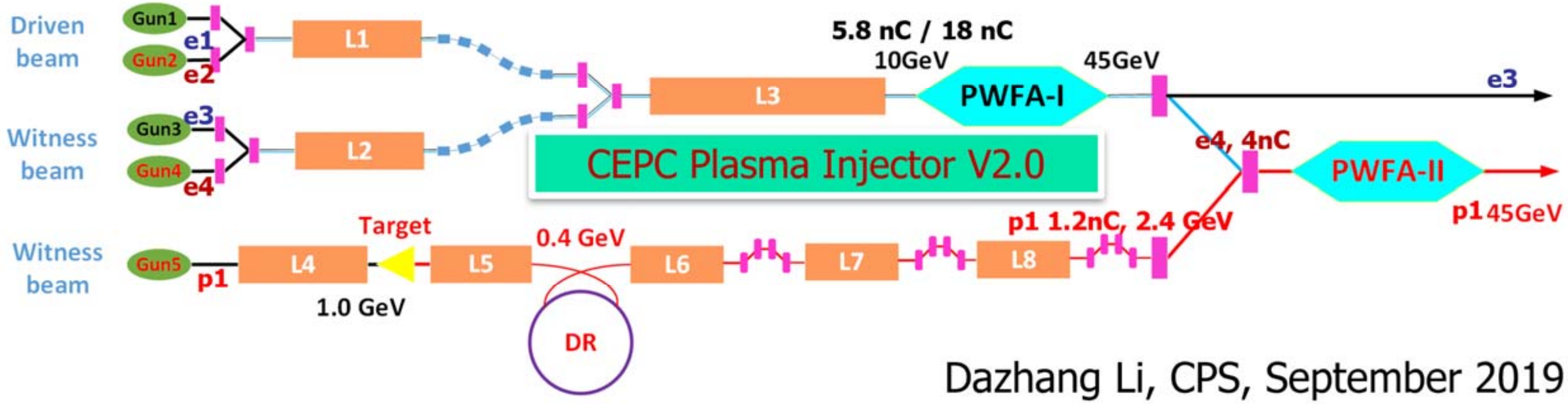
CPI e- acceleration: error tolerance analysis

Offset (x direction)
Bunch charge [nC]
Energy [GeV]
RMS energy spread





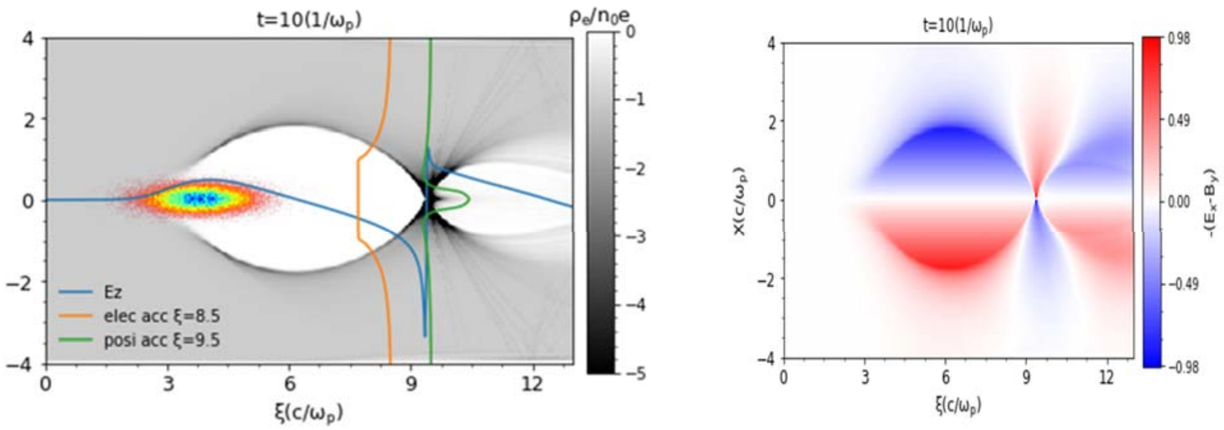
Tilt angle
Bunch charge [nC]
Energy [GeV]
RMS energy spread



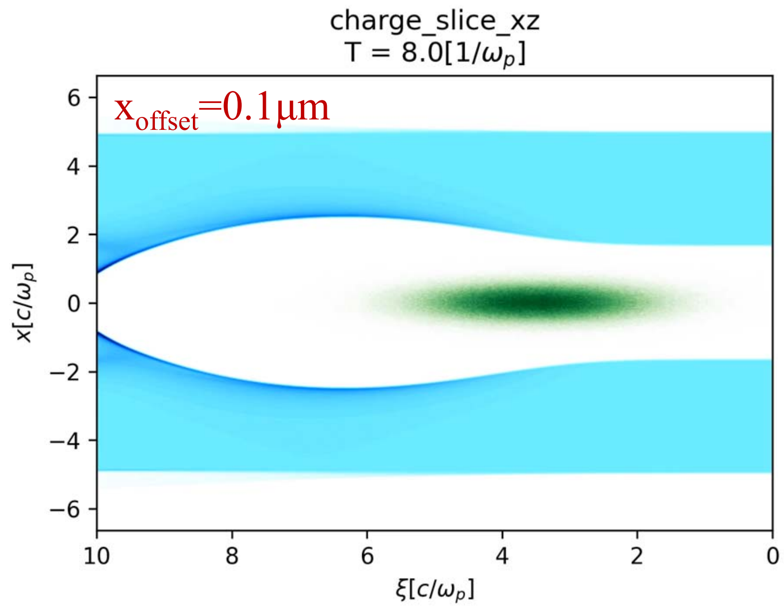
CPI e+ acceleration: stable & high efficiency

A "perfect" wakefield means:

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



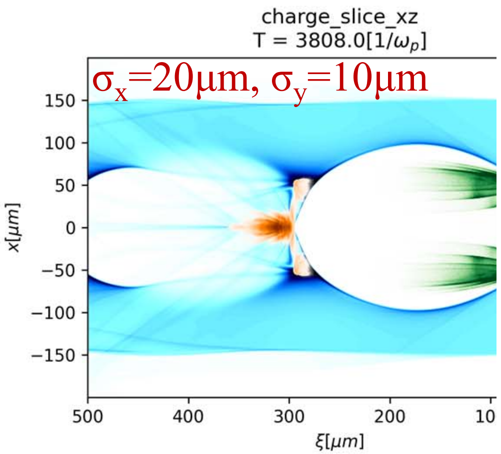
So, the blowout wakefield in uniform plasmas is quite fit for e- acceleration, while unfit for e+ acceleration

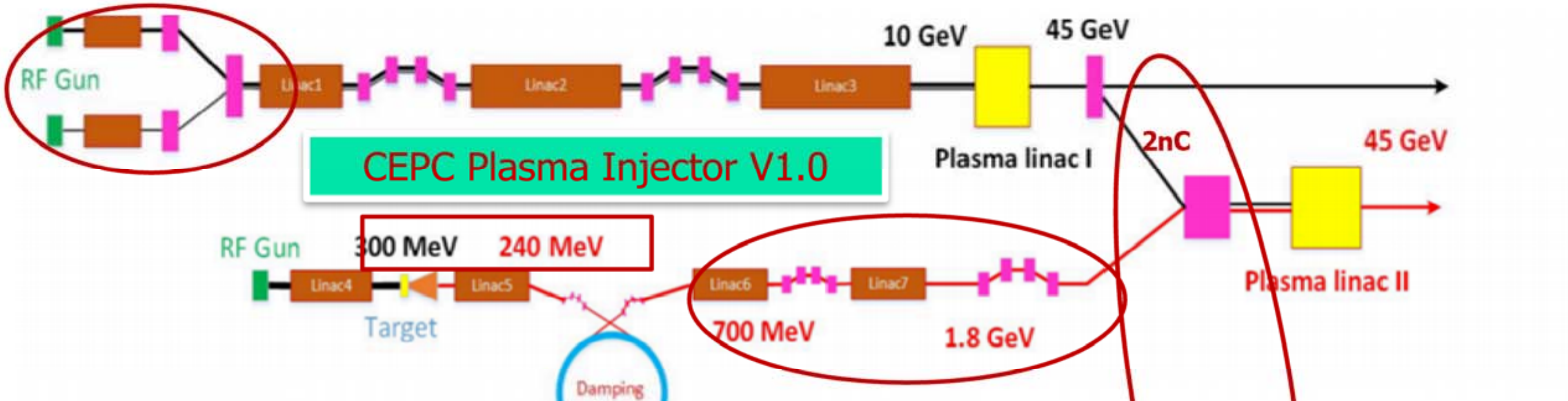


- **High efficiency 60%**
- **Low energy spread ~0.5%**
- **Small emittance growth**
- **Need e- driver, e+ trailer and plasma channel exactly coaxial**

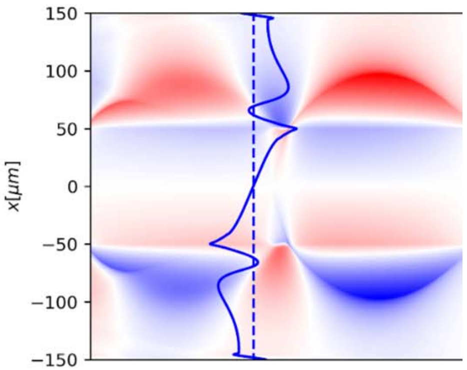
Shiyu Zhou, W. Lu et al., CEPC Conceptual Design Report (2018)

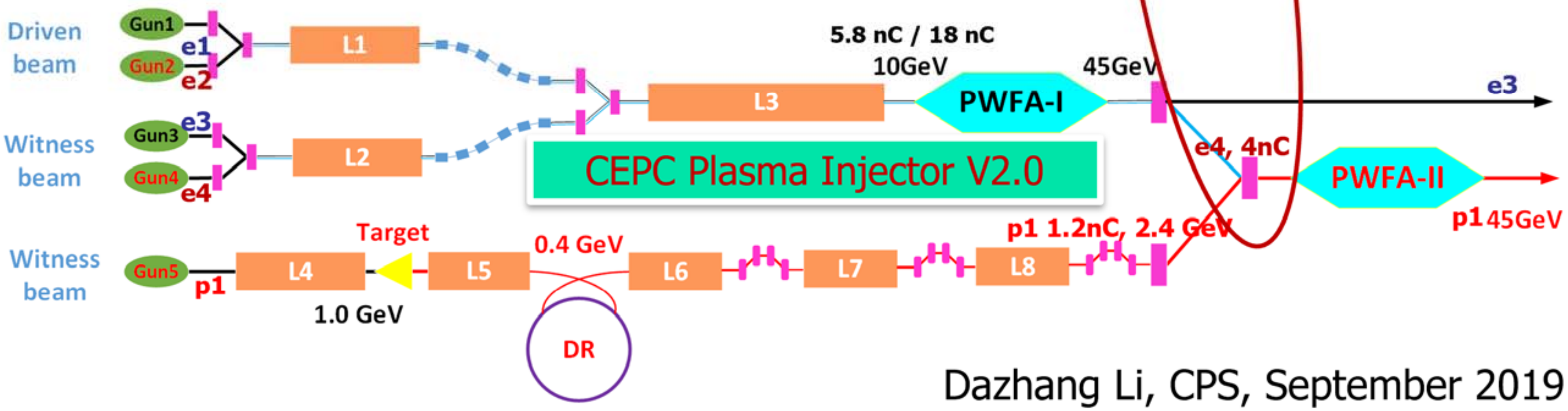
CPI e+ acceleration: stable & high efficiency





Jianfei Hua, AAC, August 2018



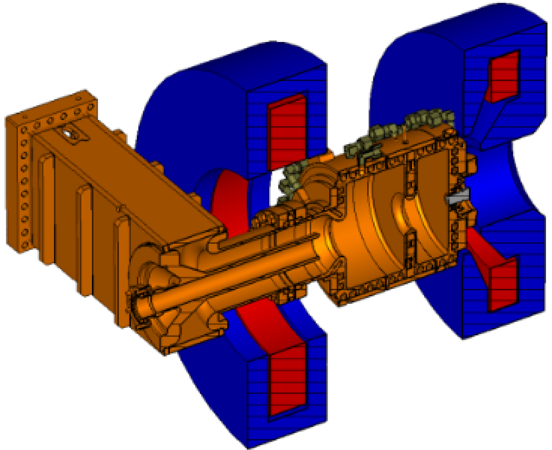


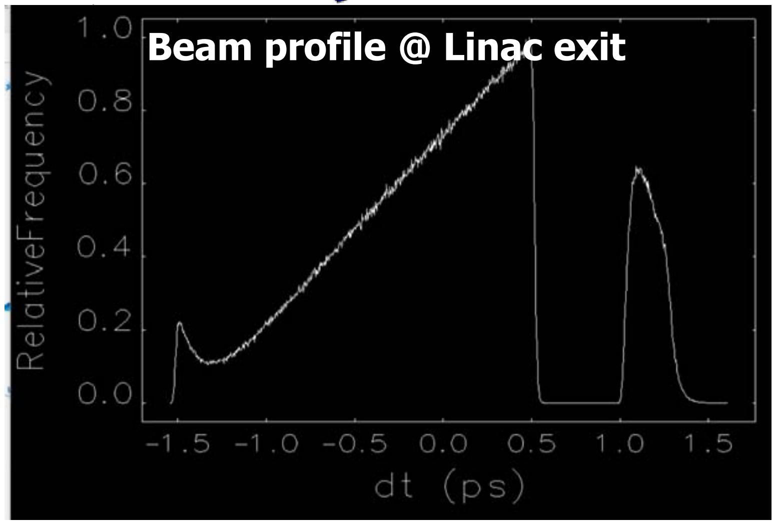
Dazhang Li, CPS, September 2019

Shi

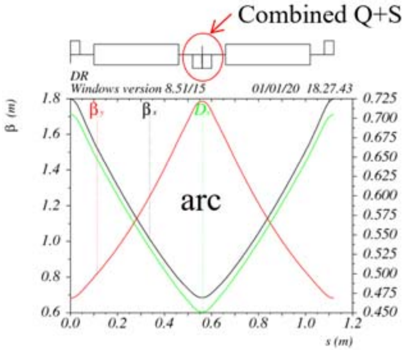
The linac design and optimization for CPI

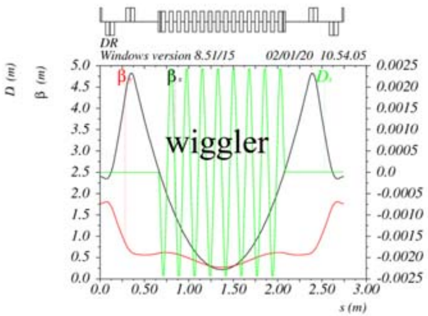
10nC, shaped, L-band e- photocathode Gun

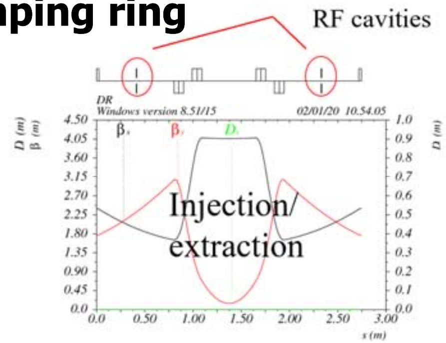


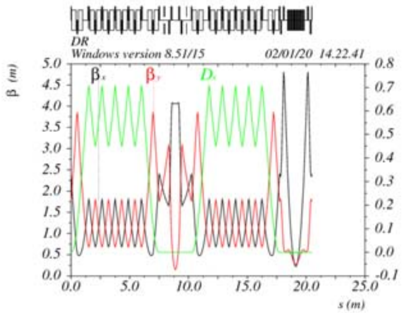


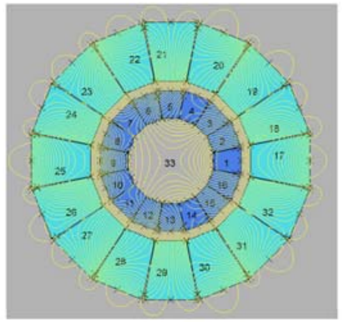
e+ beamline and damping ring

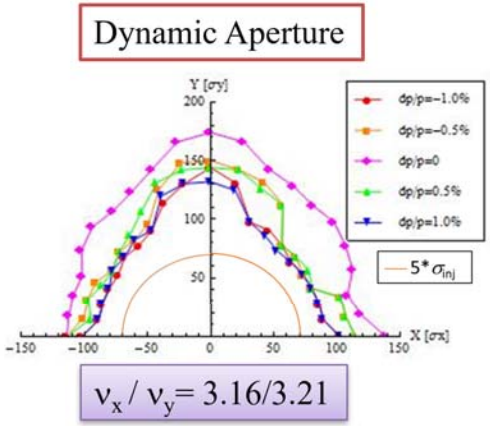






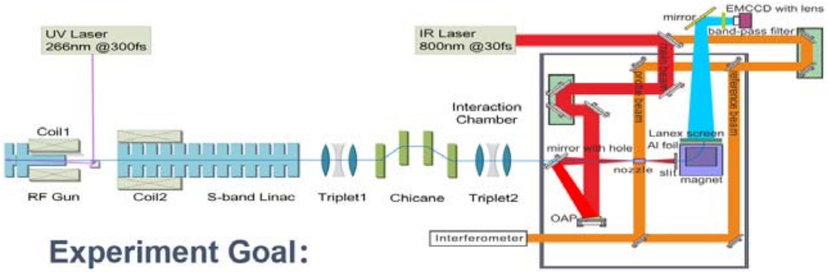






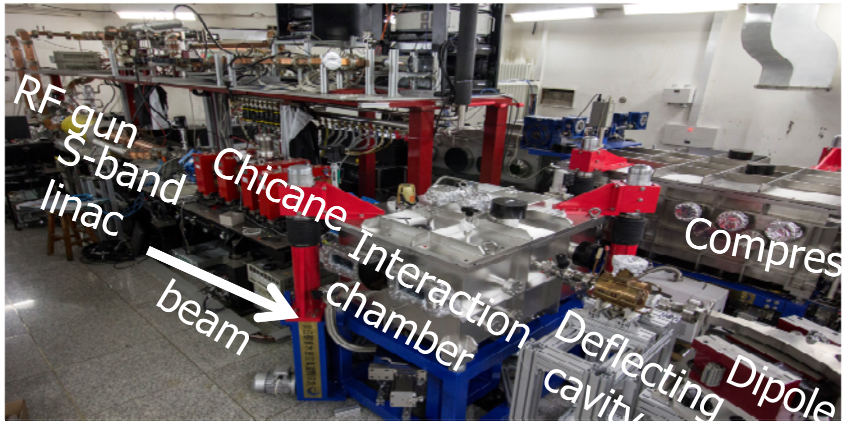
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

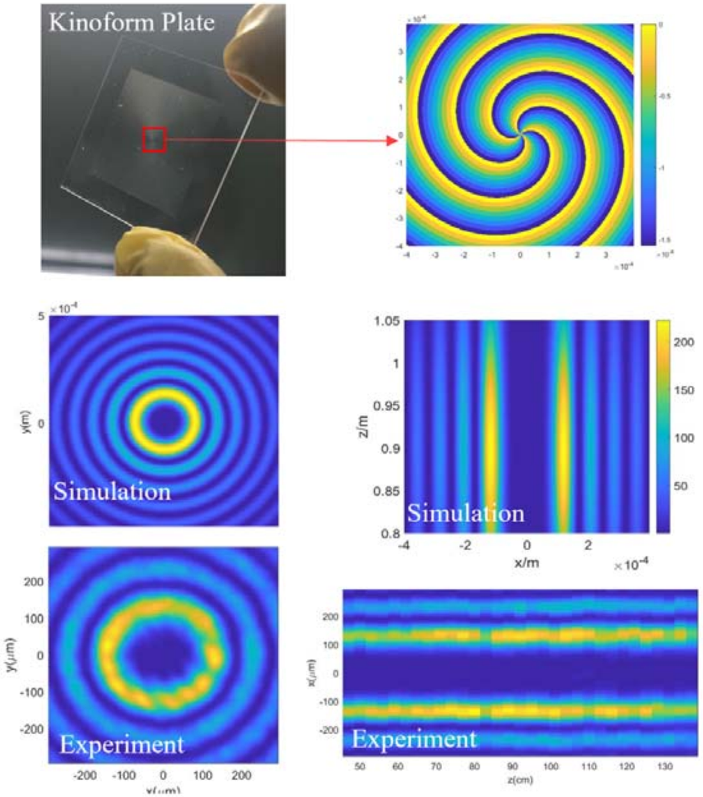
Key technique – passive plasma dechirper

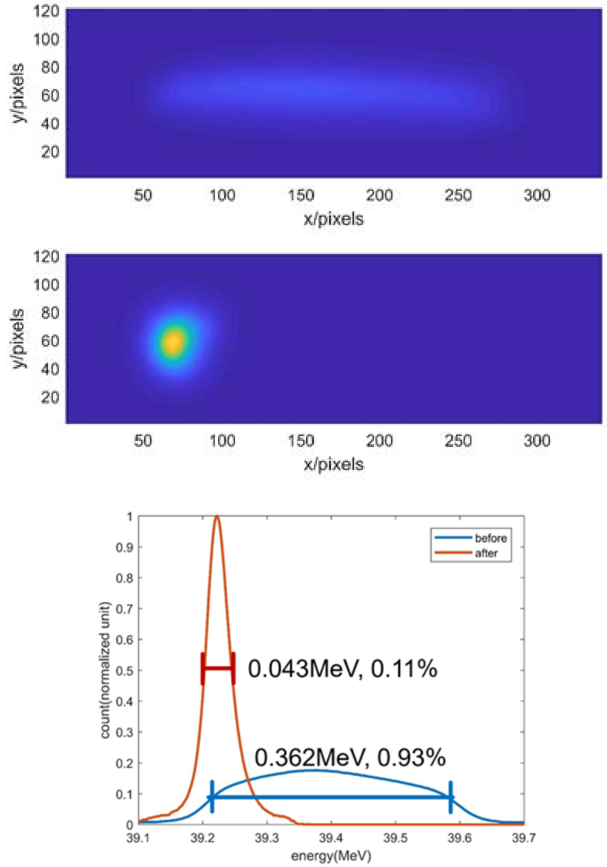


Experiment Goal:

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)

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- Introduction to CEPC & CPI
- Current status of CPI studies
- **Roadmap and proposed test facilities**

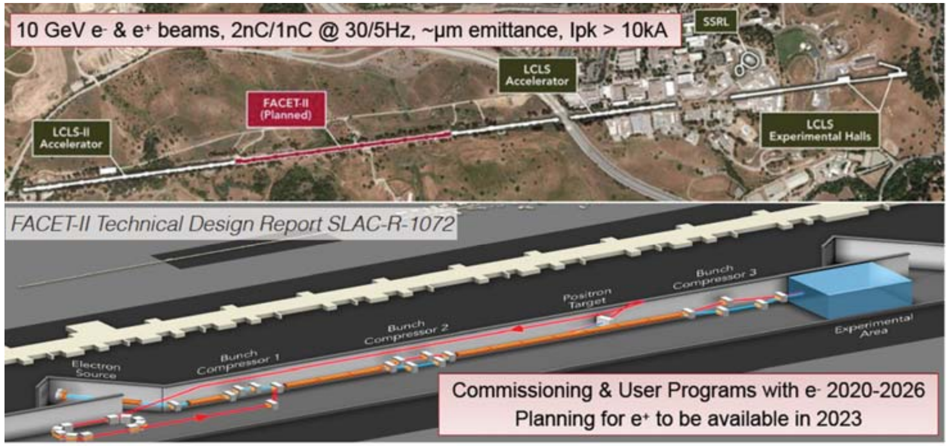
Key issues of CPI

Key issues		Preliminary study/ Conceptual design	Detailed and convincing simulations / designs	Experiment test / Prototype
e- PWFA	HTR	√	√	×
	Beam quality preservation	√	√	×
	Error analysis	√	×	×
Conv. acc. physics and techniques	Beam profile preservation	√	×	×
	Beam merging	√	×	×
	Instrumentation	√	×	×
	Timing synchronization	√	×	×
	Positron beamline	√	√	×
Plasms source and beam manipulation	Plasma dechirper	√	√	√
	Plasma lens	×	×	×
	Plasma sources	√	√	×
	Staging	√	×	×

Biggest uncertainty: lack of experimental test

Need a dedicated PWFA test facility for CPI!

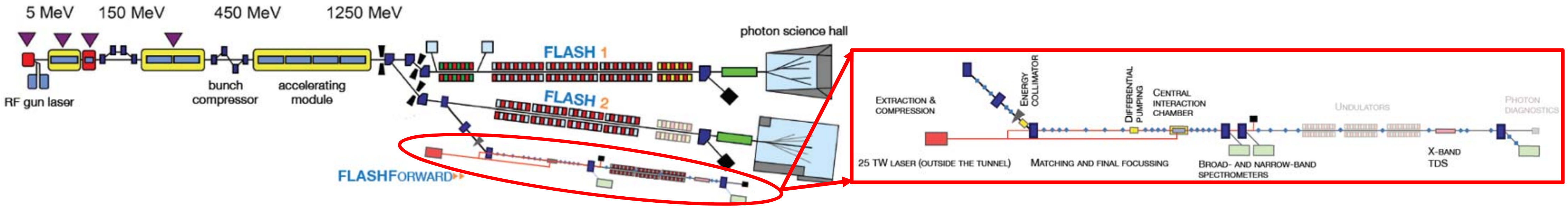
Principles of CPI TF: unique and cost-effective



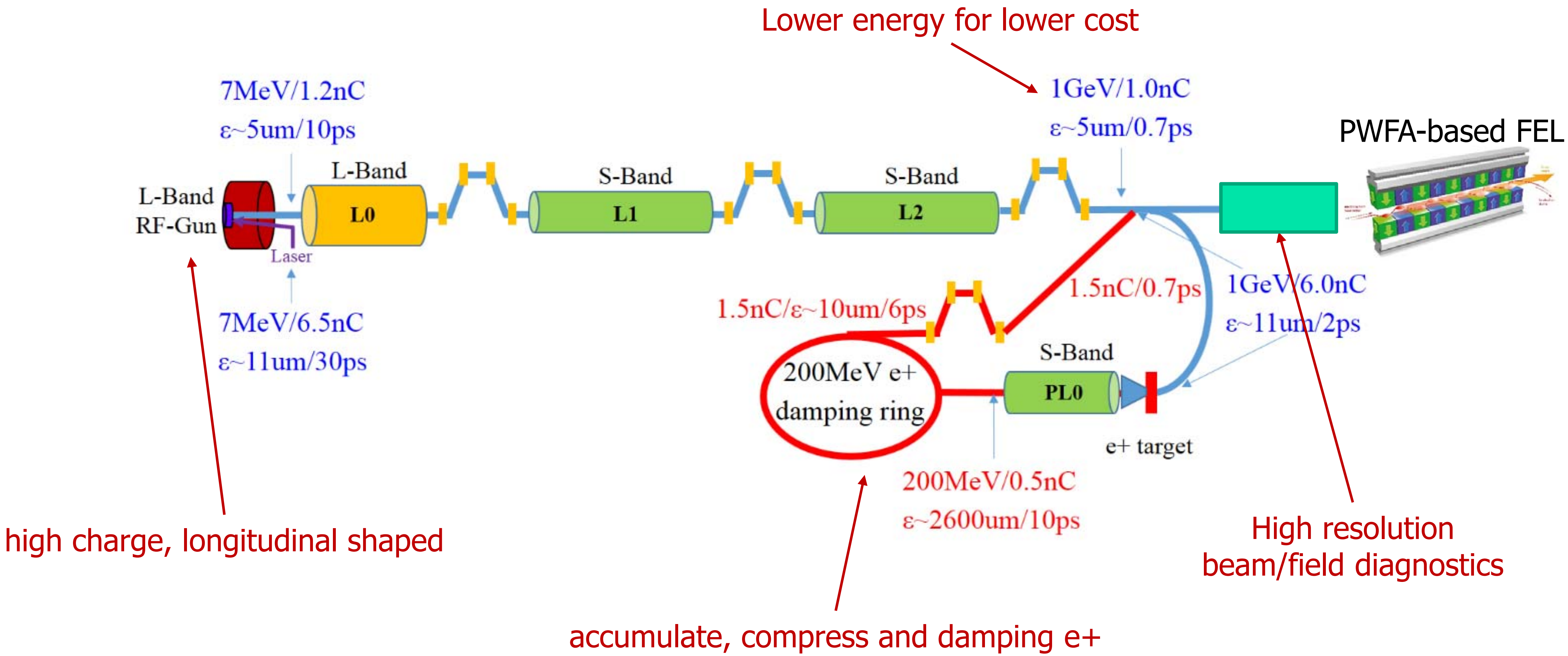
Electron Beam Parameter	Baseline Design	Operational Ranges	Positron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5	Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5	Charge per pulse [nC]	1	0.7-2
Repetition Rate [Hz]	30	1-30	Repetition Rate [Hz]	5	1-5
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	4.4, 3.2	3-6	Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	10, 10	6-20
Spot Size at IP $\sigma_{x,y}$ [μm]	18, 12	5-20	Spot Size at IP $\sigma_{x,y}$ [μm]	16, 16	5-20
Min. Bunch Length σ_z (rms) [μm]	1.8	0.7-20	Min. Bunch Length σ_z (rms)	16	8
Max. Peak current I_{pk} [kA]	72	10-200	Max. Peak current I_{pk} [kA]	6	12

Principles of CPI TF

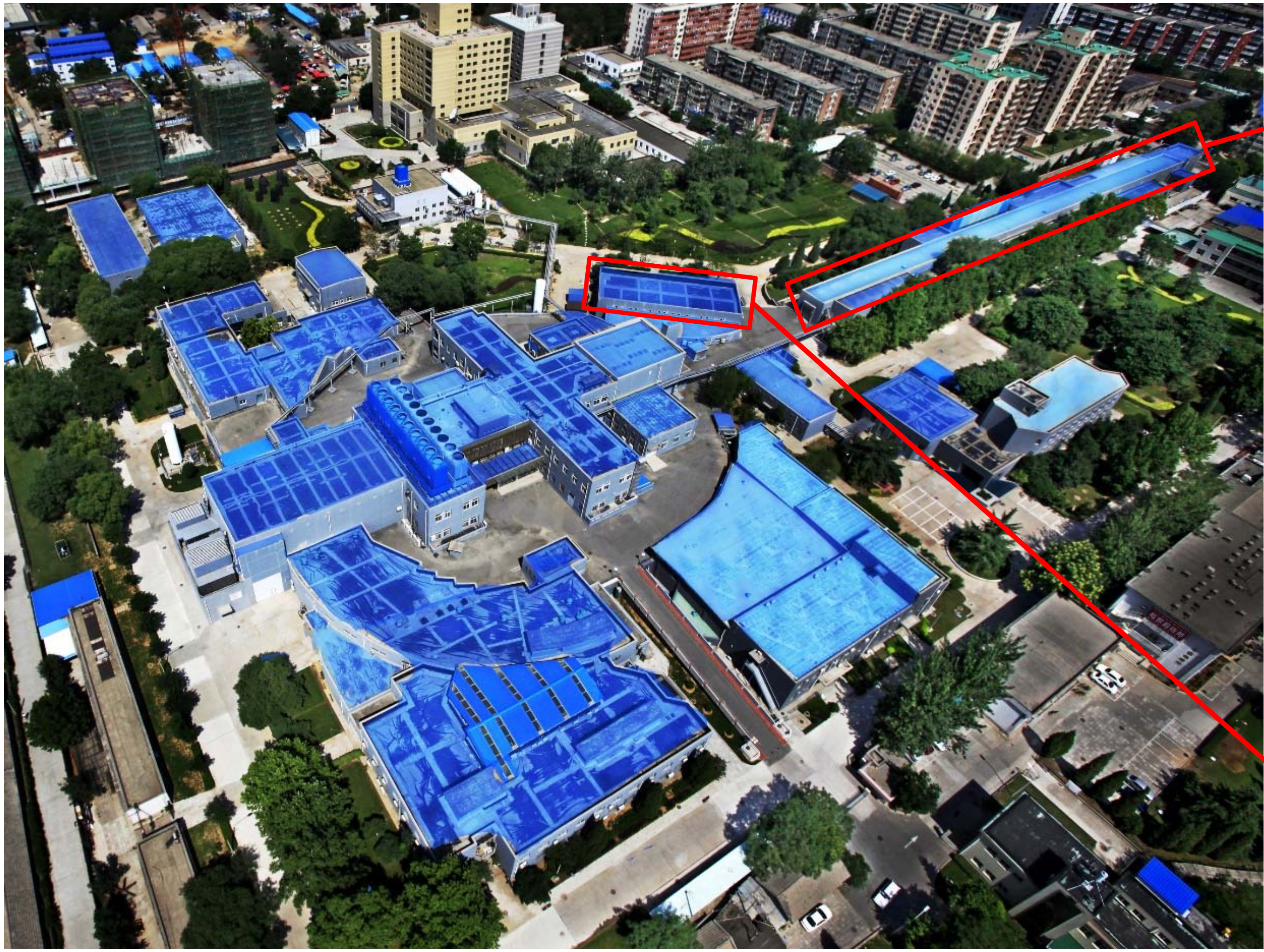
1. MUST including e+ beamline
2. High charge (10+ nC) L-band RF Gun needed
3. Staging of different types of accelerators
4. As low energy (cost) as possible
5. PWFA-based FEL studies included
6. $I_{peak} \geq 3kA$; $n_b \geq n_p (10^{16} cm^{-3})$ → 3kA @ 10μm×10μm



Conceptual design of CPI TF (~500M CHY)

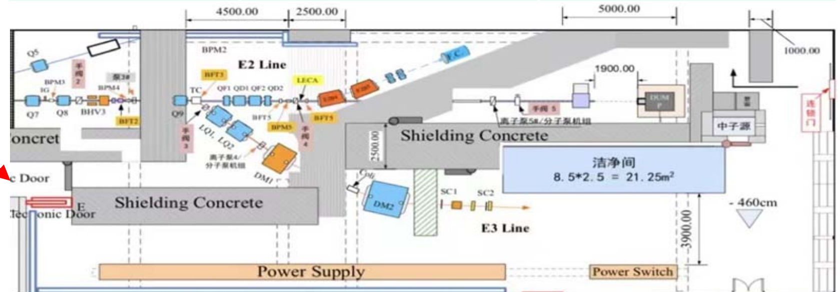


PWFA TF based on BEPC-II linac (~100M CHY)



BEPC-II linac (200m)

	e-	e+
Energy	≤ 2.5 GeV	≤ 2.5 GeV
Geometry Emittance	0.1 mm·mrad	0.4 mm·mrad
Peak current	0.5 kA	~ 0.01 kA
Bunch charge	2 nC	＜ 0.1nC
Beam size	1.1mm×1.1mm	2mm×2mm
Energy spread	0.5%	0.5%

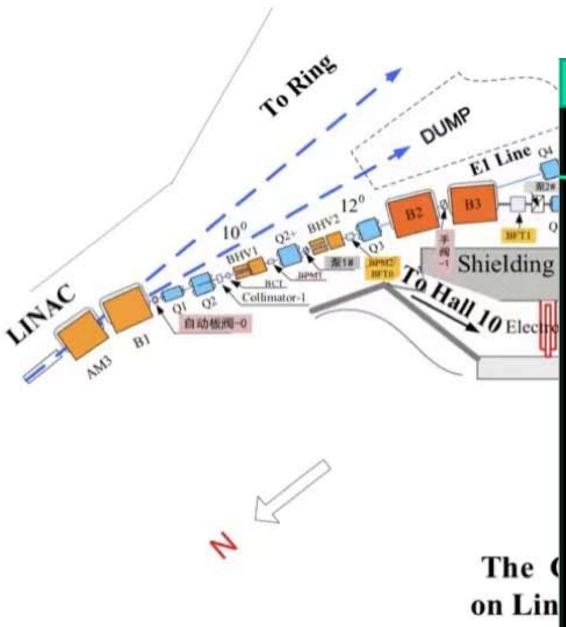


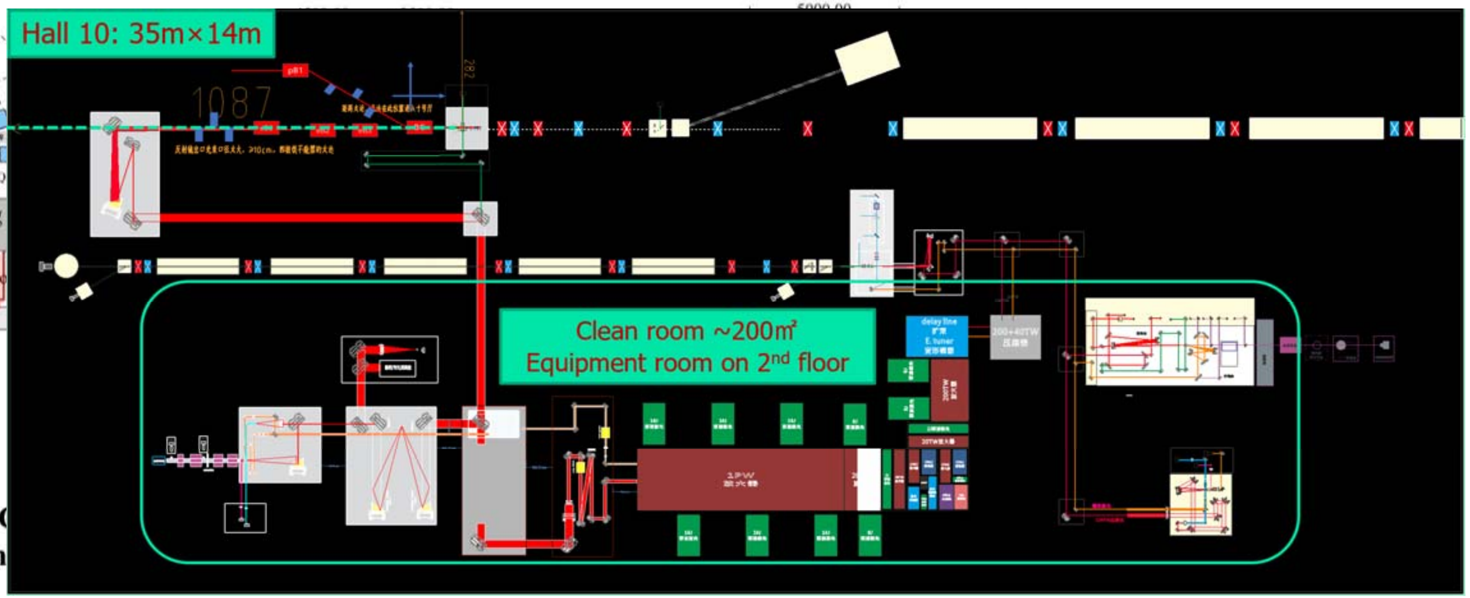
Experimental Hall: 35m × 14m

Timetable for Exp. Hall re-construction

- **Phase I (2023-2024):**
  - New transport beamline installation & commissio
  - New Final Focus system in Exp. Hall (beam size
  - Clean room + laser system installation + laser-b
  - 10+ nC L-band RF gun design

Beams in P1	e0	e1	p1	eL
Energy	≤ 2.5 GeV	/	≤ 2.5 GeV	≤ 0.5 GeV
Peak current	0.5 kA	~ 2 kA	~ 0.1 kA	≥ 5kA
Bunch charge	2 nC	2nC	< 0.1nC	0.2nC
Focal spot	1.1mm	50μm	50μm	1μm
Energy spread	0.5%	0.5%	0.5%	< 5%
Profile	Gaussian	Gaussian	Gaussian	Gaussian





Timetable for Exp. Hall re-construction

- **Phase II (2025-2027):**
  - L-band RF gun fabrication and test
  - Beam, plasma and laser diagnostics system installation
  - PWFA experiments with moderate intensity e- beam
- **Phase III (2027-):**
  - RF gun installation and linac upgrade (beam size 0.1 mm → 0.01 mm, peak current 2 kA→ 6 kA)
  - New e+ beamline installation (damping ring
  - PWFA experiments with e+ beam and high ir
  - PBA based FEL studies

Phase II & III	e1	e2	p2	eL
Energy	/	≤ 2.5 GeV	~ 0.6 GeV	≤ 0.5 GeV
Peak current	~ 2 kA	≥ 6 kA	~ 3 kA	≥ 5kA
Bunch charge	2nC	10 nC	~ 1 nC	0.2nC
Focal spot	50μm	< 10μm	< 20μm	1μm
Energy spread	0.5%	/	/	< 5%
Profile	Gaussian	triangle	Gaussian	Gaussian

Key issues studied at different phase (not only for CPI)

Phase I	e0	e1	p1	eL
Energy	≤ 2.5 GeV	/	≤ 2.5 GeV	≤ 0.5 GeV
Peak current	0.5 kA	~ 2 kA	~ 0.1 kA	≥ 5kA
Bunch charge	2 nC	2nC	< 0.1nC	0.2nC
Focal spot	1.1mm	50μm	50μm	1μm
Energy spread	0.5%	0.5%	0.5%	< 5%
Profile	Gaussian	Gaussian	Gaussian	Gaussian

Phase II & III	e1	e2	p2	eL
Energy	/	≤ 2.5 GeV	~ 0.6 GeV	≤ 0.5 GeV
Peak current	~ 2 kA	≥ 6 kA	~ 3 kA	≥ 5kA
Bunch charge	2nC	10 nC	~ 1nC	0.2nC
Focal spot	50μm	< 10μm	< 50 μm	1μm
Energy spread	0.5%	/	/	< 5%
Profile	Gaussian	triangle	Gaussian	Gaussian

Research		driver	trailer
e- PWFA	① blowout acc.	e1 or eL	
	③ HTR acc.	e2	e1 or eL
e+ PWFA	① acc. structure	e1	/
	① preliminary acc.	eL	p1
	③ High quality acc.	e2	p2
Conv. acc. physics & techniques	② L-band RF gun test	/	/
	③ Beam profile	e2	/
	① Beam merging	e1/eL	
	② Instrumentation	eL	/
	② Synchronization	eL	e1/e2
	③ e+ beamline	p2	/
Plasms source and beam manipulation	① Dechirper	e1/eL	/
	② Plasma lens	/	/
	① Plasma sources	/	/
	③ Staging	e1, e2, eL	

Summaries and prospects

- **CPI e- acceleration**
  - New baseline for CPI e- acceleration fixed (10 GeV → 30 GeV, TR ~ 2)
  - Overall start-to-end simulation is ongoing, will get results before TDR
  - No extra damping mechanisms besides ion motion are considered. TR≥3 is still active and investigated
- **CPI e+ acceleration**
  - Asymmetry beam scheme is well accepted
  - More schemes are studied, for example, TR~2 e+ acceleration
- **Experiments studies recovered now, waiting for beamtime**
  - Plasma dechirper experiment got good results, and experiment on SXFEL is ongoing.
  - A dedicated TF for PWFA is crucial, and a TF based on BEPC-II is in promoted step by step
- **CPI is still at conceptual design stage, and still has a big gap to TDR or EDR stage compared with other mature systems. No showstoppers till now**
- **CPI is a middle step, not a finish line. HTR (TR≥3) + Staging = 120/180 GeV Full energy injection, even future PWFA collider !**

Thank you!