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

Recent Progress on CEPC Plasma Injector

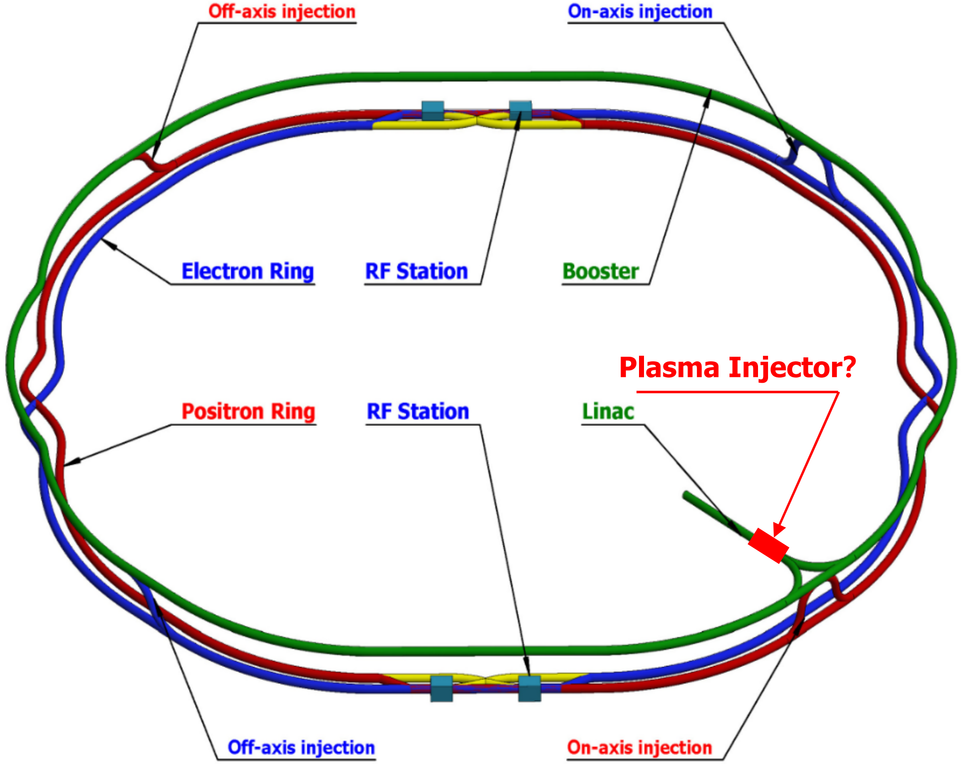
Prof. Wei Lu, Dr. Dazhang Li, et al.

On behalf of the IHEP-THU-BNU AARG team

Outlines

- Introduction to CEPC & CPI
- Recent Progress on CPI
- Summaries and Prospects

100 km Booster → Low field dipole problem



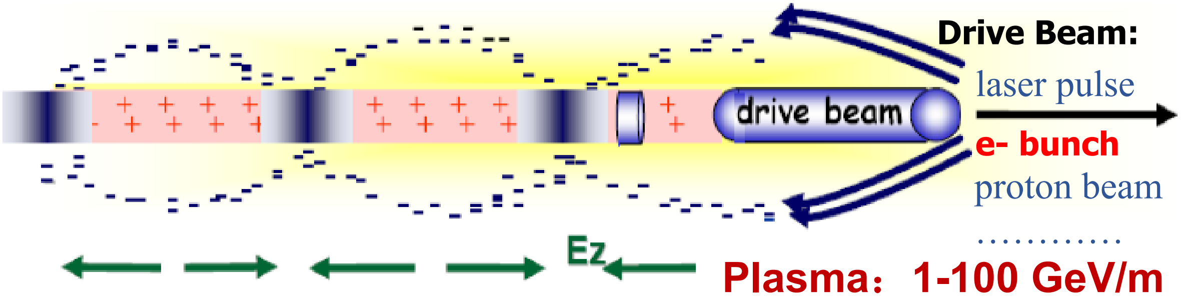
10 GeV e-/e+ beam in a 100 km ring

- 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.

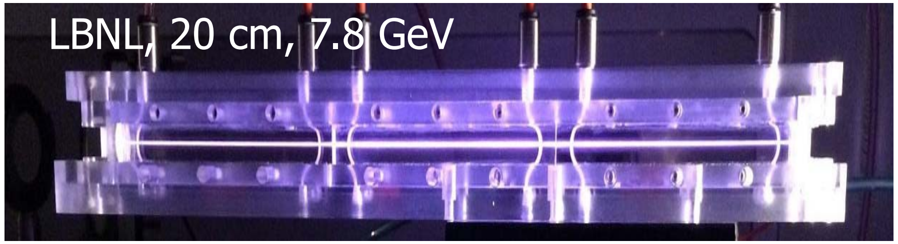
10 GeV Linac → **100 km Booster** → **e- ring** / **e+ ring**

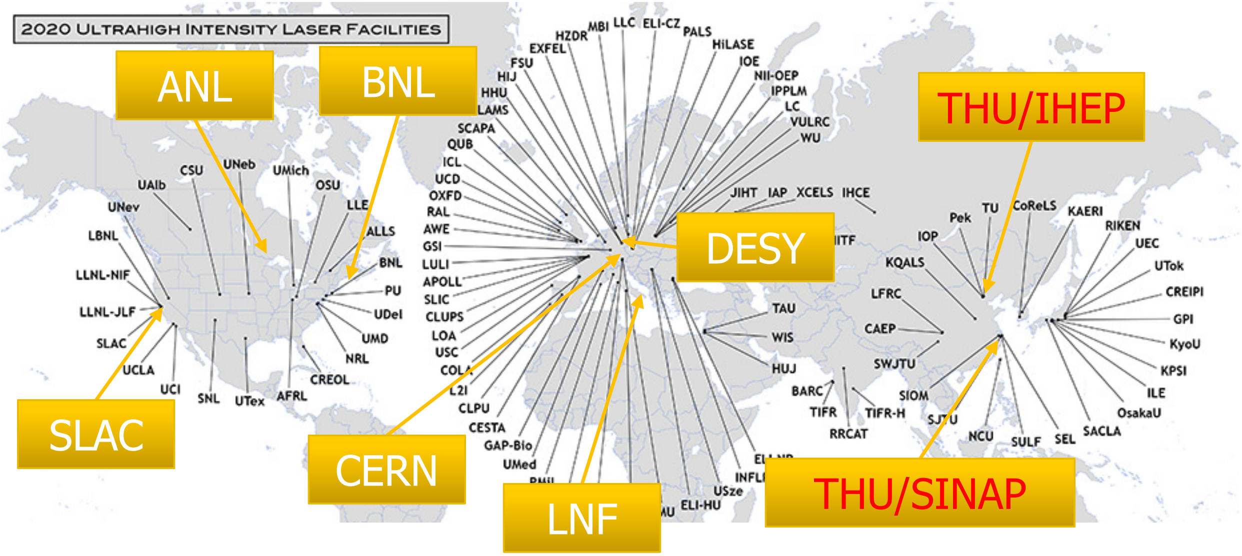
10 GeV linac + CT coil magnet, or
30 GeV linac + iron-core magnet ?
Both lead to significant cost rise ~ 1 B RMB

Plasma acceleration: > 1000 gradient increase



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





Affiliations/institutes on PWFA Study

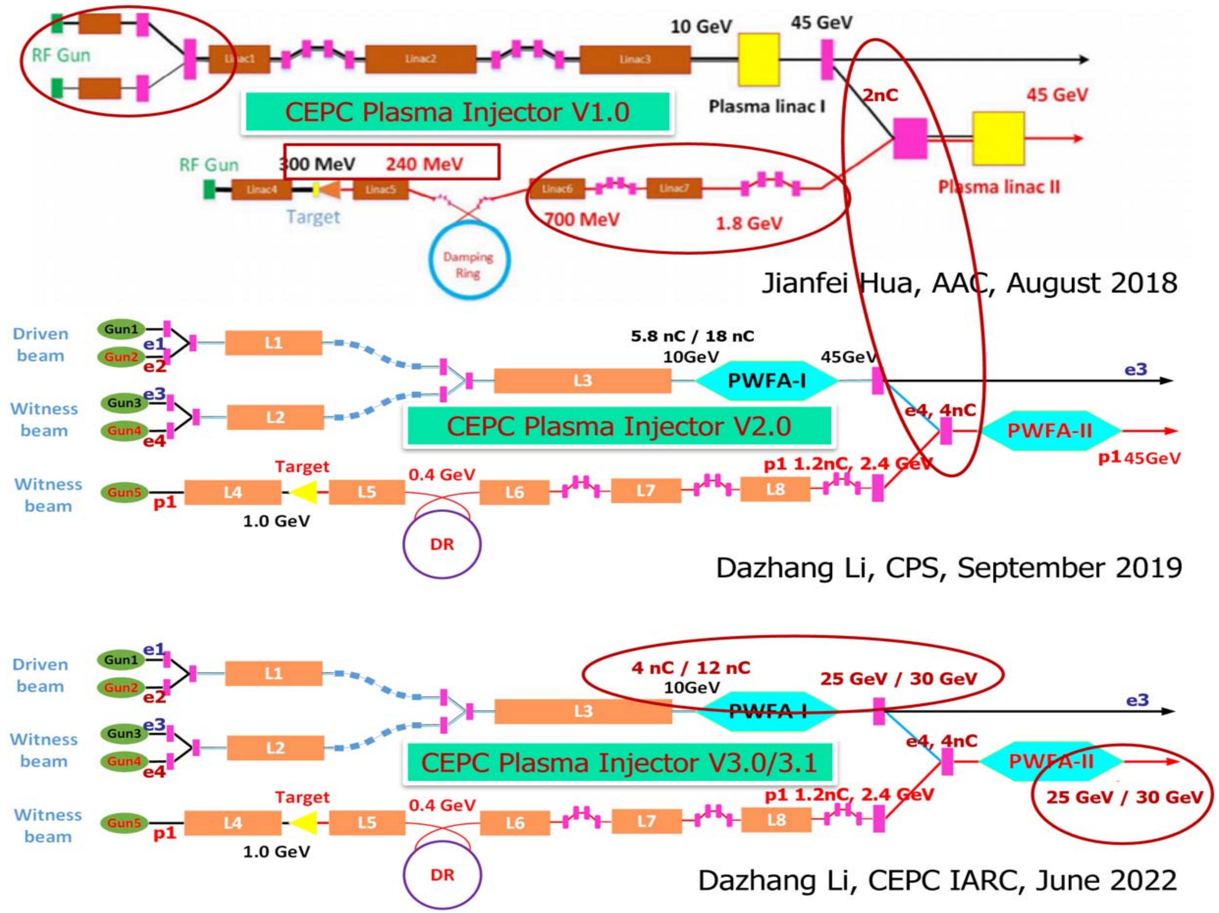
CPI: CEPC Plasma Injector, since 2017

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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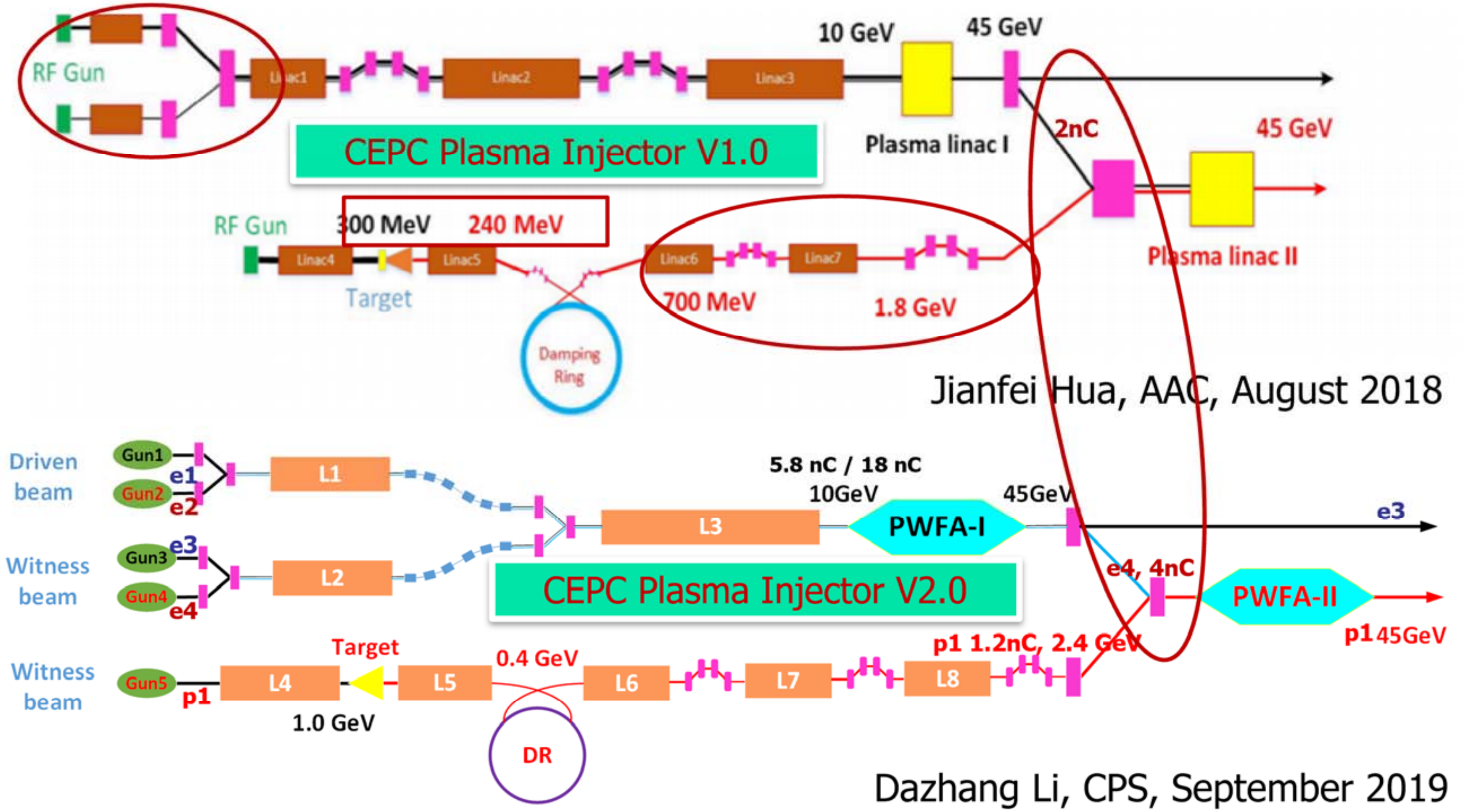
Conceptual design V1.0 → V2.0: e+ acceleration



Conceptual design V1.0 → V2.0: e+ 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

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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.

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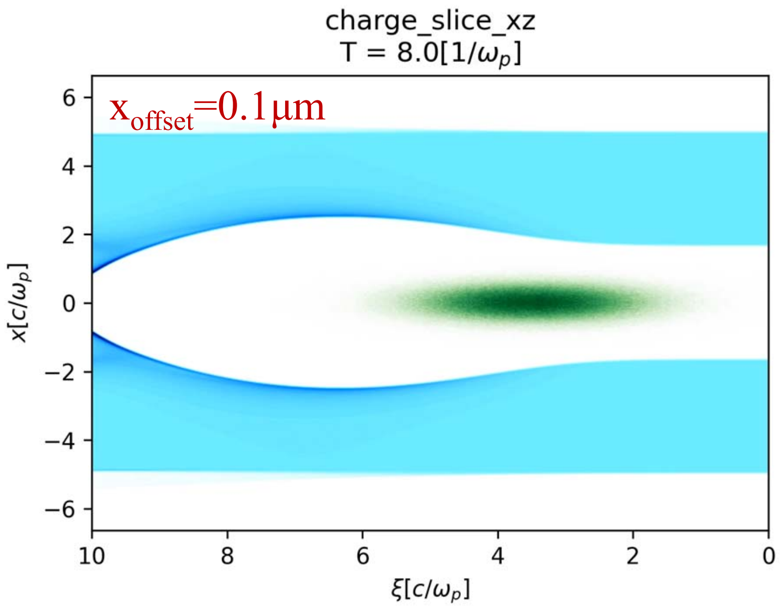
Gradient~5GeV/m,

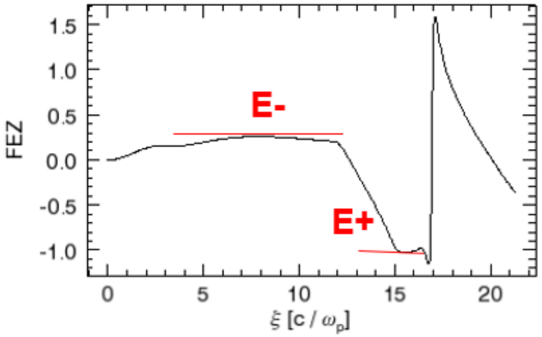
Efficiency >30%,

Energy Spread~1.5%



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

Conceptual design V2.0 → V3.0: transformer ratio



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

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

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

For CPI V1.0 and V2.0

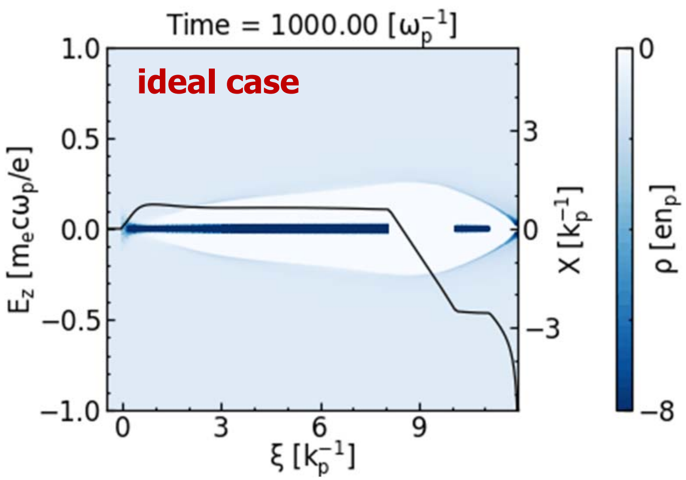
TR ≥ (45.5-10)/10=3.55

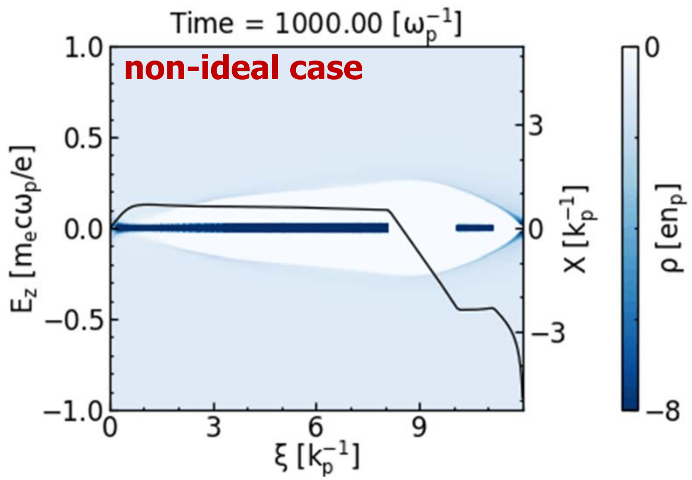
V2.0 TR≥3.5

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

The noise is over estimated because the simulation particle number is much smaller than real particle number





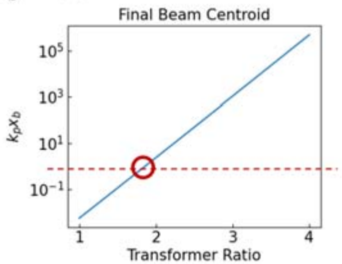
Conceptual design V2.0 → V3.0: transformer ratio

- 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

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

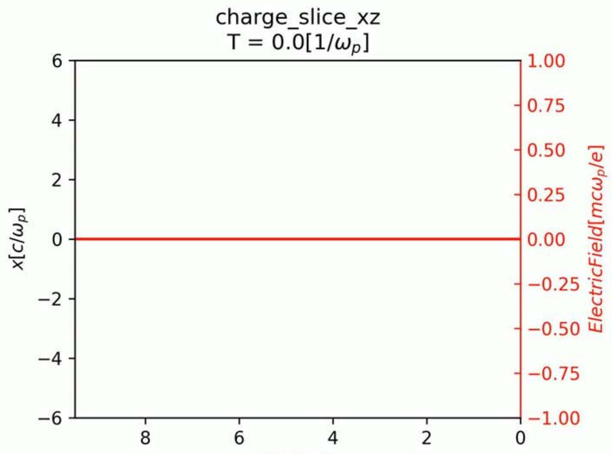
➢ For a 10GeV driver, beam size $k_p \sigma_r = 0.2$, c=0.7, $c_b = 0.8$



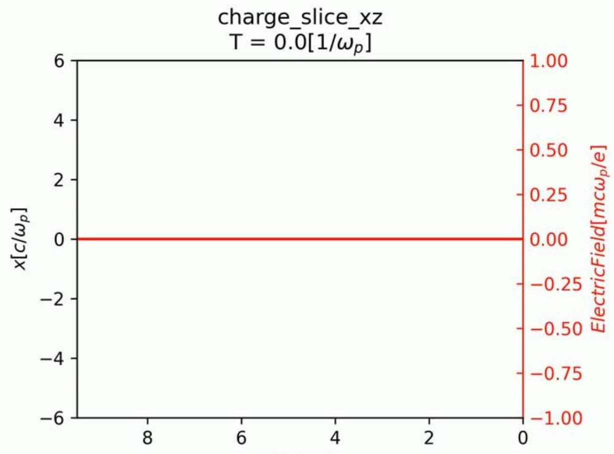
TR ≤ 1.8 seems acceptable ($x_b < 1$) if no extra damping mechanism is adopted.

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

Ion motion can significantly decrease the hosing instability

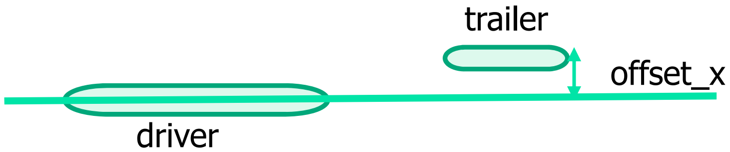


TR=2 without ion motion

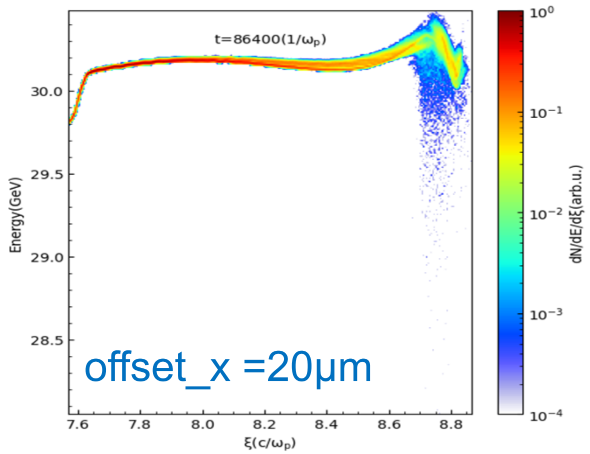


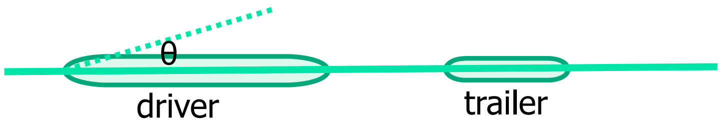
TR=2 with ion motion

Conceptual design V2.0 → V3.0: transformer ratio

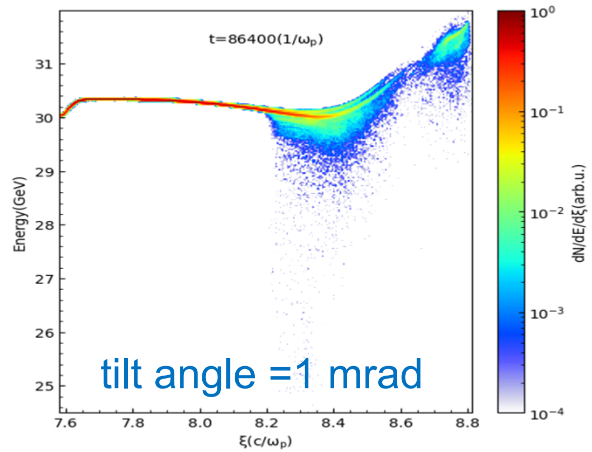


Offset (x direction)	4 μm	12 μm	20 μm	30 μm
Bunch charge [nC]	1.197	1.197	1.174	1.079
Energy [GeV]	30.01	30.04	30.16	30.37
RMS energy spread	0.43	0.41	0.22	0.72



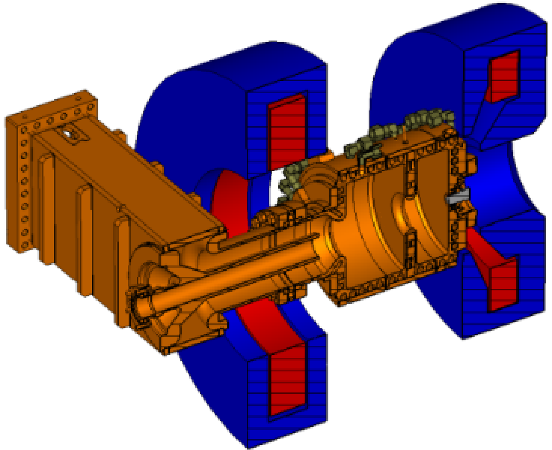


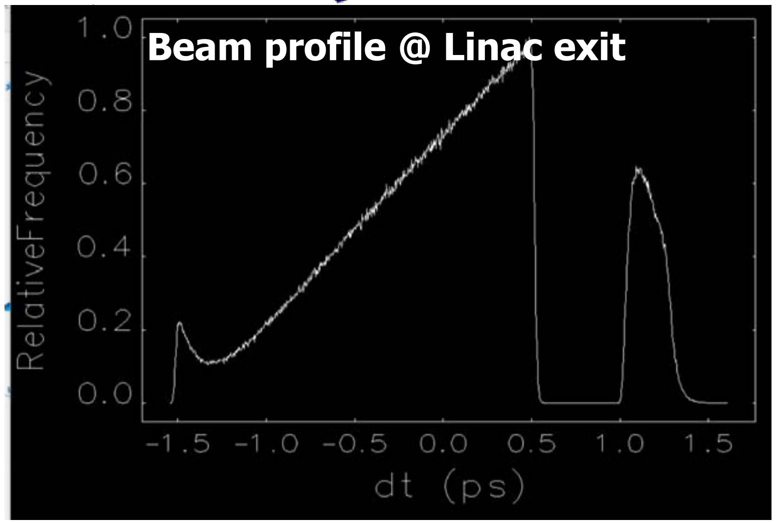
Tilt angle	10 μrad	100 μrad	1 mrad
Bunch charge [nC]	1.197	1.197	0.903
Energy [GeV]	30.01	30.01	30.24
RMS energy spread	0.41	0.41	0.65



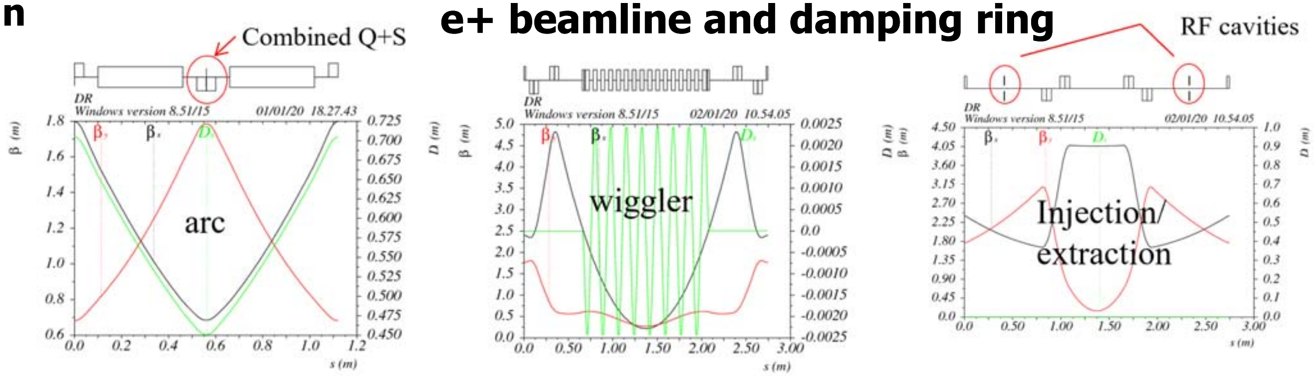
The linac design and optimization for CPI

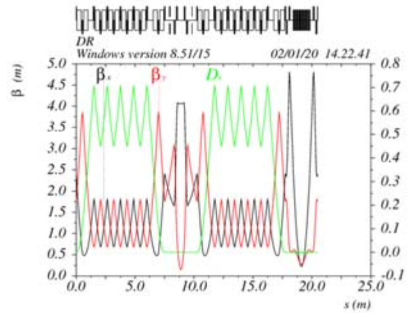
10+ nC, shaped, L-band e- photocathode Gun

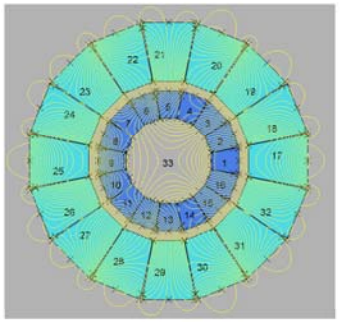


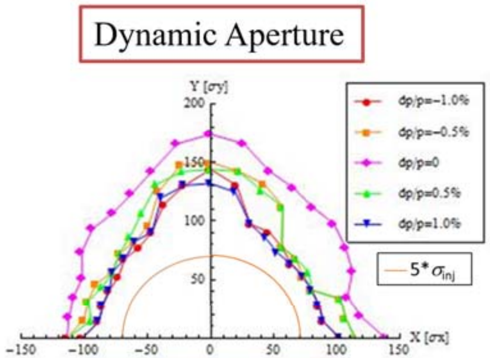


e+ beamline and damping ring





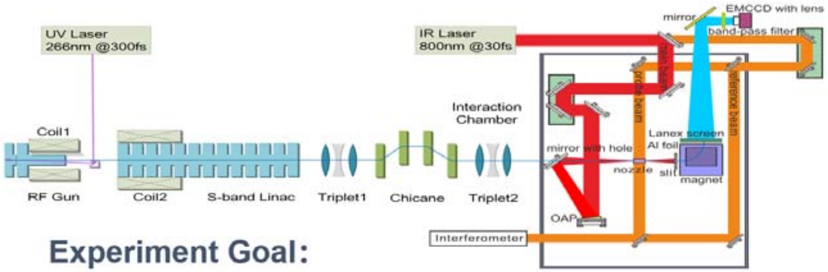




$\nu_x / \nu_y = 3.16/3.21$

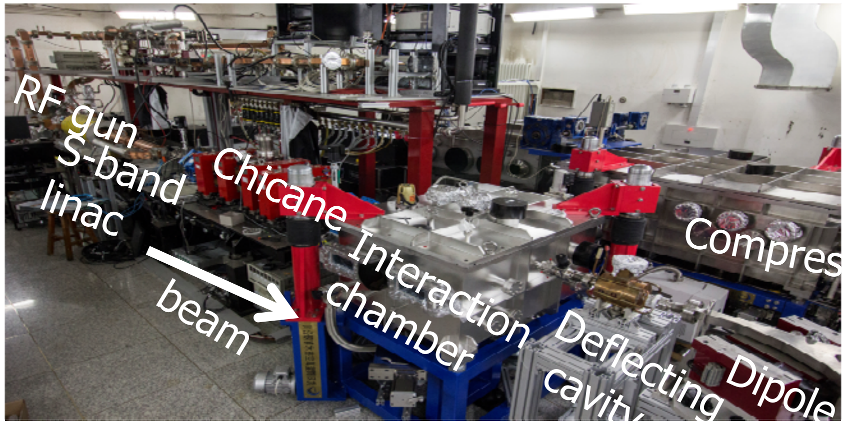
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

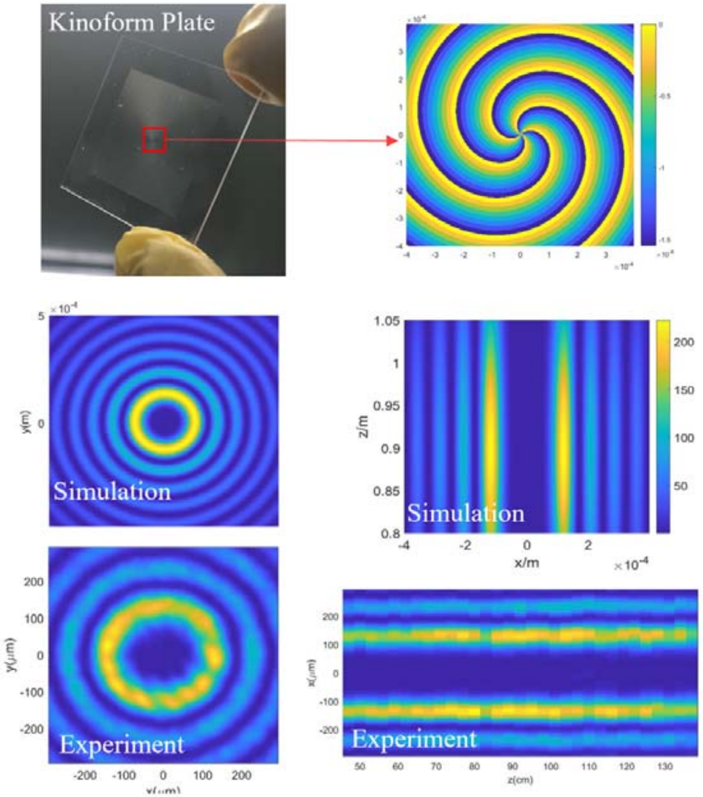
Key experimental progress on CPI – plasma dechirper

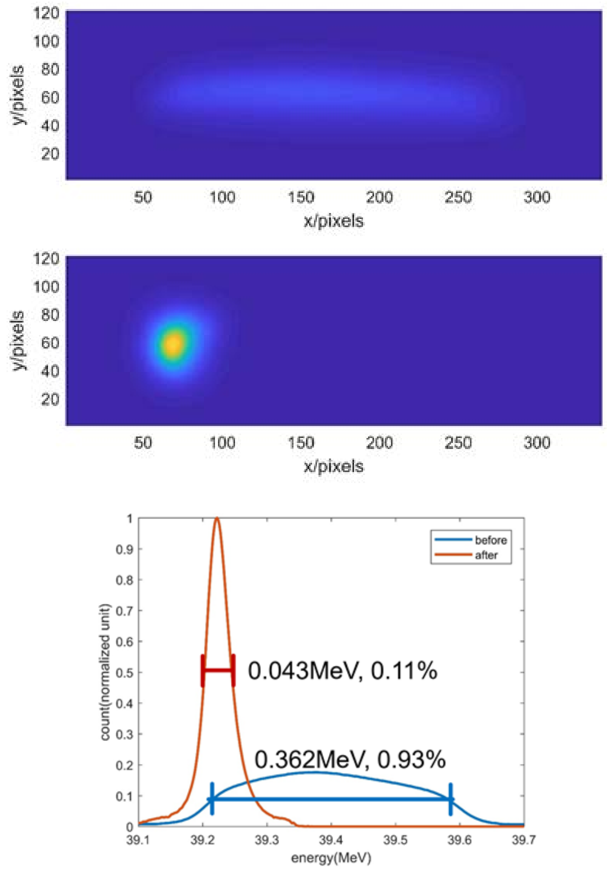


Experiment Goal:

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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Key issues on CPI studies

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

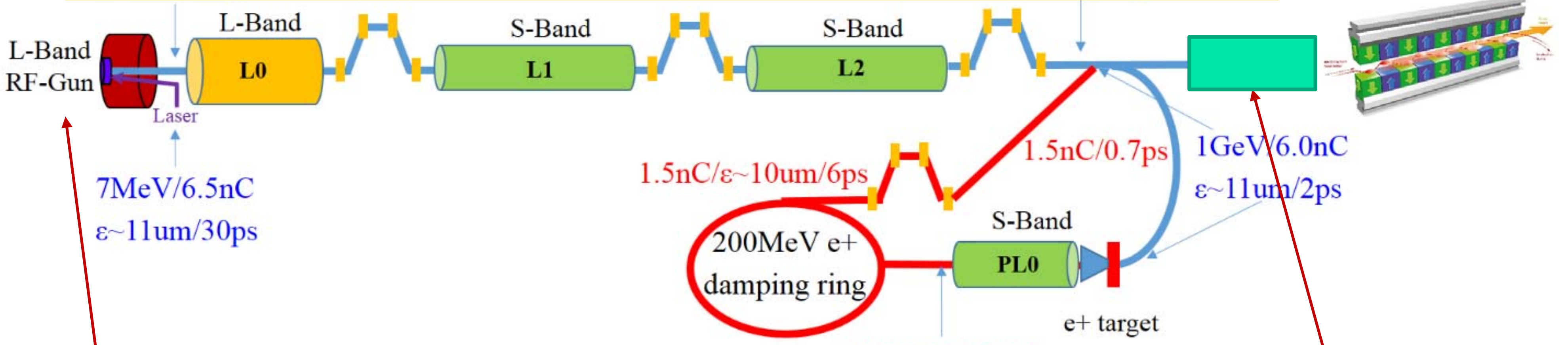
Need a dedicated PWFA test facility for CPI!

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

Preliminary design for a plasma acceleration TF

Lower energy for lower cost

Total Budget: ≥ 300,000,000 RMB



high charge, longitudinal shaped

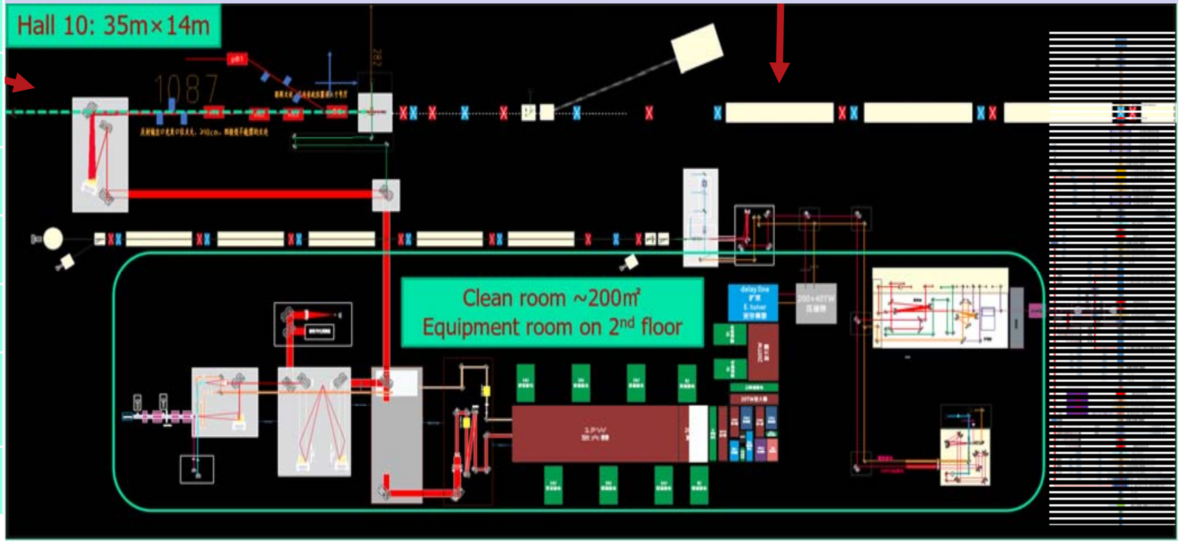
High resolution beam/field diagnostics

accumulate, compress and damping e+

TF based on BEPC-II linac and HPL (from THU)

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
Phase 2 & 3	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

- **Aims of the test facility**
  - **Combination of BEPC-II linac and laser system (2-3 years)**
  - **L-band e- Gun design and fabrication (2-3 years)**
  - **High efficiency HTR (>1) PWFA experiment (2-3 years)**
  - **Damping ring installation and e+ acc. exp. (3-5 years)**
  - **PBA-based FEL studies (3-5 years)**



Summaries and prospects

- **CPI HTR e- acceleration**
  - TR~2 scheme seems acceptable
  - More damping mechanisms are under consideration. TR≥3 is still alive
  - Overall start-to-end simulation is ongoing
- **CPI e+ acceleration**
  - Asymmetry beam scheme is well accepted, more schemes are studied, HTR e+ acc. included
  - Proposals were submitted to FACET-II committee, waiting for beam time
- **Experiments time is insufficient**
  - Plasma dechirper experiment got good results, and experiment on SXFEL is ongoing.
  - A dedicated TF for PWFA is crucial, we are working on it
- **CPI is still at conceptual design stage, and still has a big gap to TDR or EDR stage compared with other mature systems. No stoppers till now. We, the IHEP-THU-BNU collaborated team, will keep working on it.**

Thank you!