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Road map for the plasma acceleration technology at CEPC

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On behalf of the IHEP-THU-BNU AARG team

June 10, 2022

Outlines

- CPI progress since last IARC (Oct. 2021)
- 2021 IARC review report on CPI
- Key technology for CPI and our road map

Low field Dipole Problem in Booster

➢ Challenges:

- Field error <29Gs*0.1%=0.029Gs → how to design
- Field reproducibility <29Gs*0.05%=0.015Gs → how to measure
- The Earth field ~0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

➢ Thinking beyond CDR

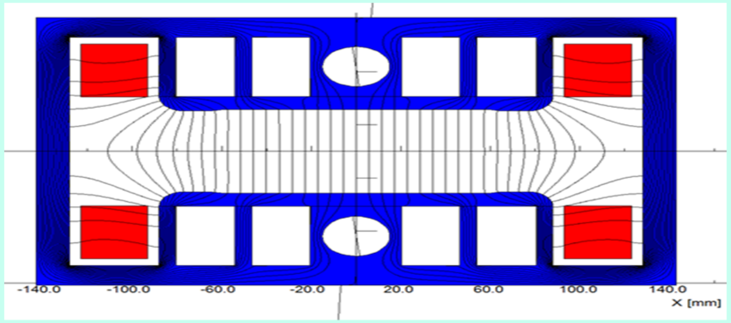
- Nominal field error: ~0.1%
- Uniformity requirement: ~0.05%
- Eddy current effect

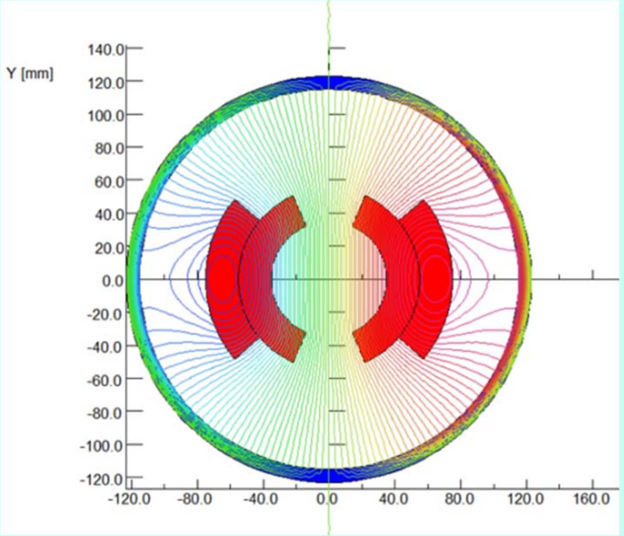
  \- Sextupole coils outside vacuum chamber

➢ Solutions in CDR

- With magnetic core (better material)
- Without magnetic core

  (Twice excitation current)



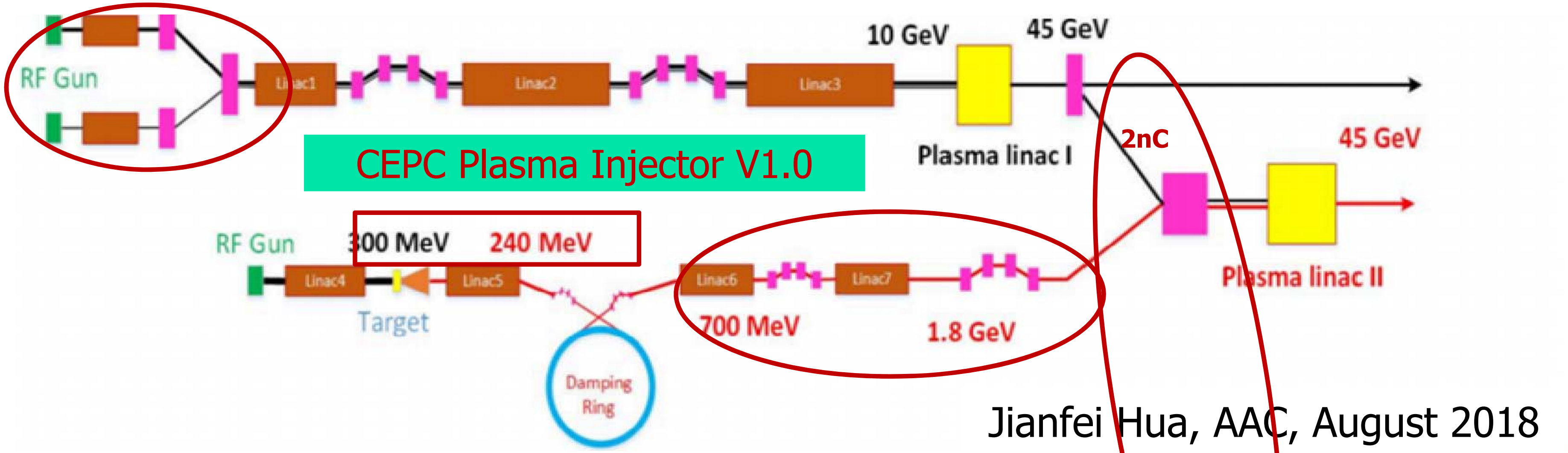


Baseline solution and cost rising

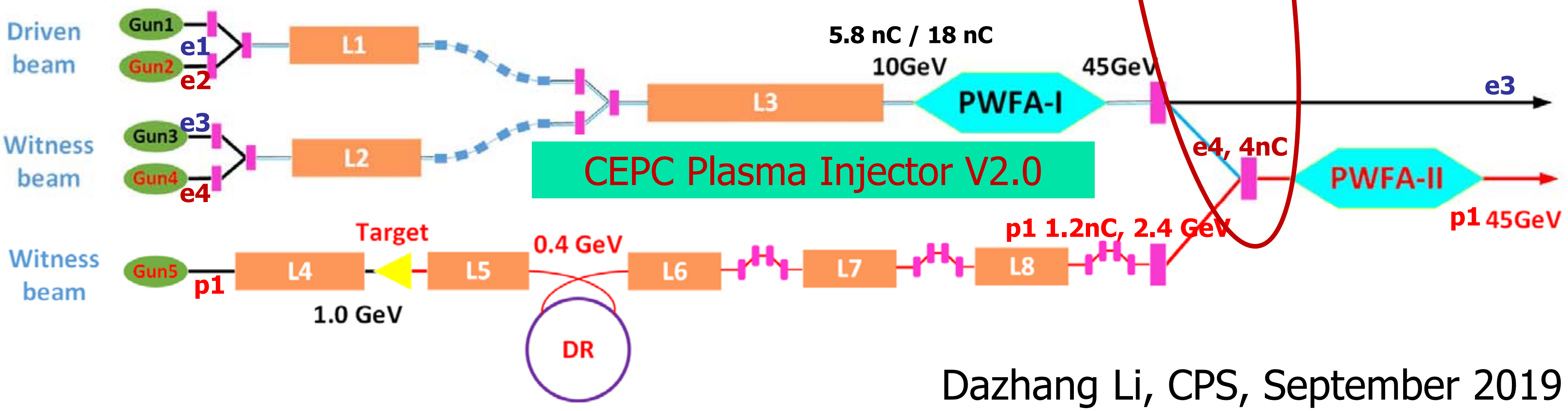
- Two kinds of the subscale prototype magnet w/wo iron cores have been developed.
- With the new baseline of 20GeV injection both prototypes full fill the requirement. But the magnet with iron cores need to use oriented silicon instead of non-oriented silicon in CDR, which leads to the cost rise
- [a]: CPI V3.0 → ↑ e-/e+ energy from 10 GeV to 30 GeV
- [b]: CPI V3.1 → ↑ e-/e+ energy from 10 GeV to 25 GeV
- [c]: Add plasma dechirper/match section, etc.
- [d]: Add 5 e- RF guns (2 L-band and 3 S-band), FF, etc.

	Booster	**Linac**
CDR	Non-oriented silicon magnet	10 GeV
New baseline	Oriented silicon magnet	20 GeV
Compared with CDR	↑ ¥ 600m	↑ ¥ 400m
Backup solution	No-iron corn magnet	10 GeV
Compared with CDR	↑ ¥ 1600m	/
CPI V3.0[a]	Non-oriented silicon magnet	10 GeV
Compared with CDR	↑ ¥ 20m[c]	↑ ¥ 100m[d]
CPI V3.1[b]	Oriented silicon magnet	10 GeV
Compared with CDR	↑ ¥ 600m ↑ ¥ 20m[c]	↑ ¥ 100m[d]

CPI conceptual Design V1.0→V2.0

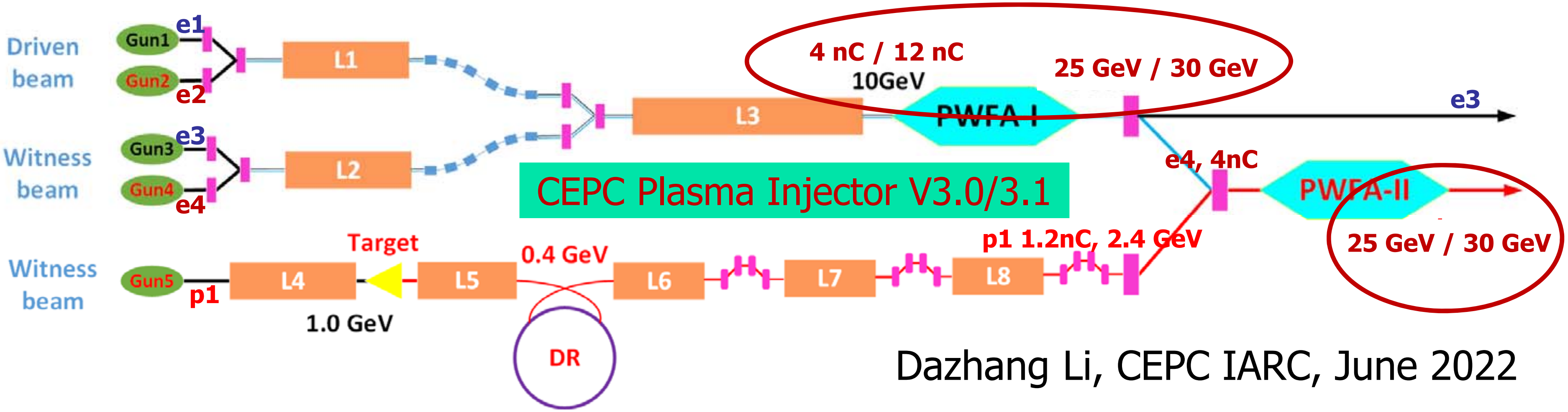


Jianfei Hua, AAC, August 2018

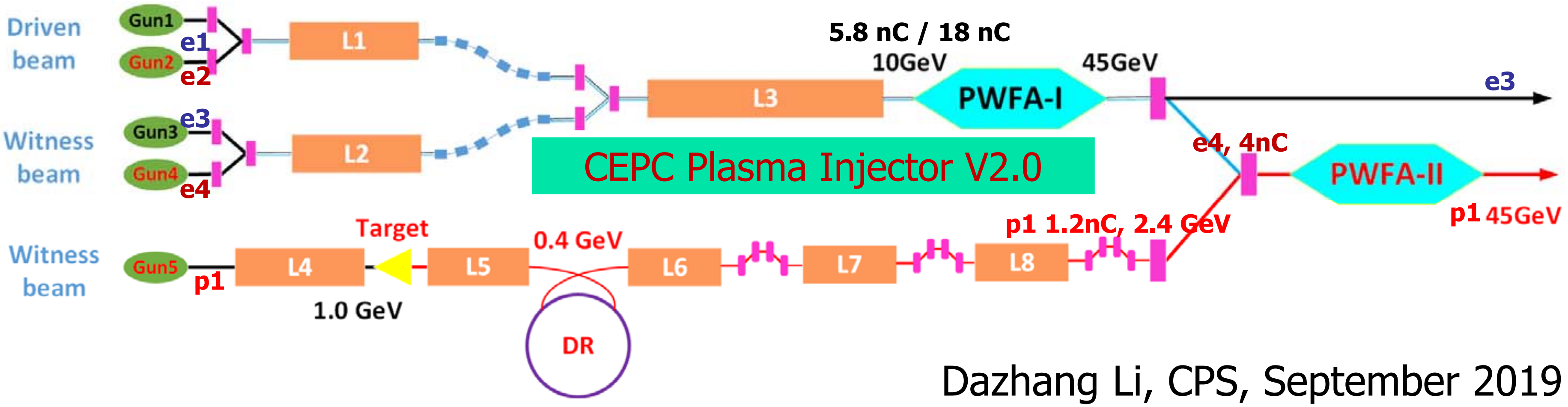


Dazhang Li, CPS, September 2019

CPI conceptual Design V2.0→V3.0/3.1

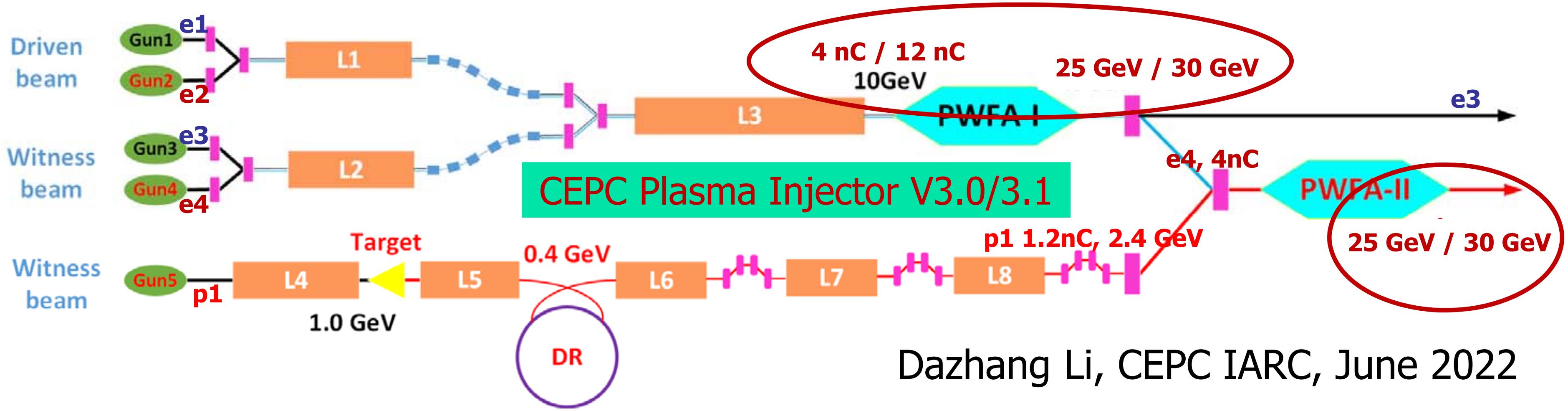


Dazhang Li, CEPC IARC, June 2022



Dazhang Li, CPS, September 2019

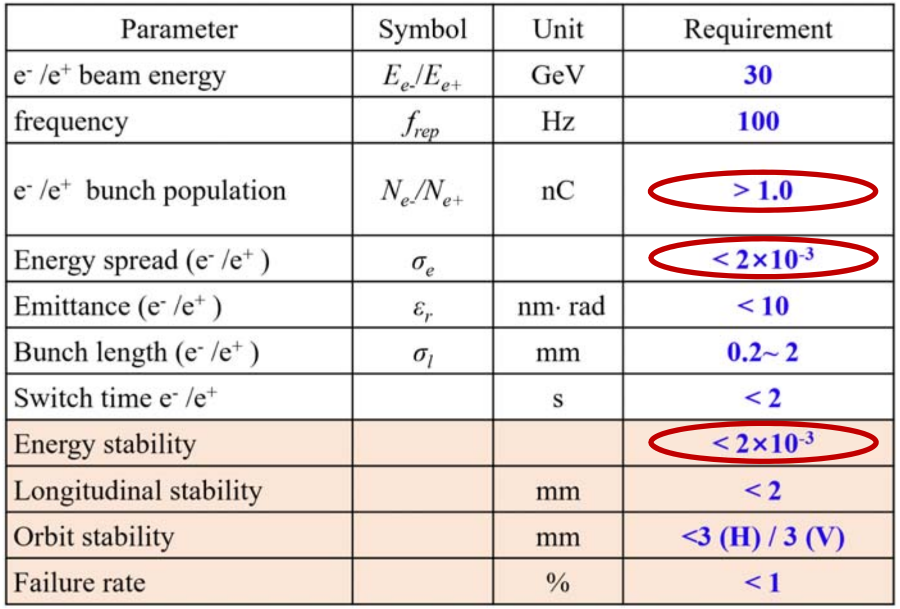
Booster requirement for 30 GeV



CEPC Plasma Injector V3.0/3.1

Dazhang Li, CEPC IARC, June 2022

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



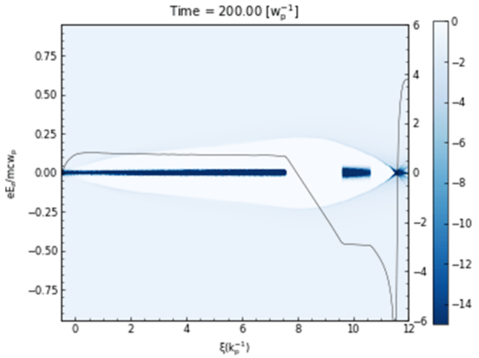
Parameter	Symbol	Unit	Requirement
e^-/e^+ beam energy	E_{e-}/E_{e+}	GeV	30
frequency	f_{rep}	Hz	100
e^-/e^+ bunch population	N_{e-}/N_{e+}	nC	> 1.0
Energy spread (e^-/e^+)	σ_e		$< 2\times10^{-3}$
Emittance (e^-/e^+)	ε_r	nm· rad	< 10
Bunch length (e^-/e^+)	σ_l	mm	0.2~ 2
Switch time e^-/e^+		s	< 2
Energy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

Ideal case for TR ≥ 1.5/2/3.5

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	

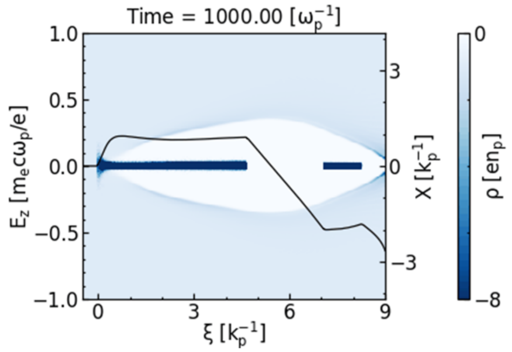
Accelerating distance (m)	10.65
Trailer energy $E(GeV)$	45.5
Normalized emittance $\epsilon_n (mm\ mrad)$	98.44
Charge(nC)	0.84
Energy spread $\delta_E(\%)$	0.56
Efficiency (%) (driver → trailer)	59.1



V3.0 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
(matched) Spot size(um)	3.89	2.75
Charge (nC)	4.0	1.2
Beam distance (um)	180	

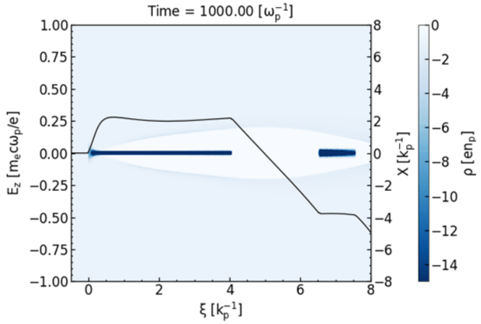
Accelerating distance (m)	6.3
Trailer energy $E(GeV)$	30
Normalized emittance $\epsilon_n (mm\ mrad)$	10
Charge(nC)	1.2
Energy spread $\delta_E(\%)$	0.32
Efficiency (%) (driver → trailer)	66.0



V3.1 TR≥1.5

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	10
Length (um)	305	80
(matched) Spot size(um)	3.89	2.75
Charge (nC)	4.63	1.5
Beam distance (um)	184	

Accelerating distance (m)	4.8
Trailer energy $E(GeV)$	25
Normalized emittance $\epsilon_n (mm\ mrad)$	10
Charge(nC)	1.5
Energy spread $\delta_E(\%)$	0.37
Efficiency (%) (driver → trailer)	52

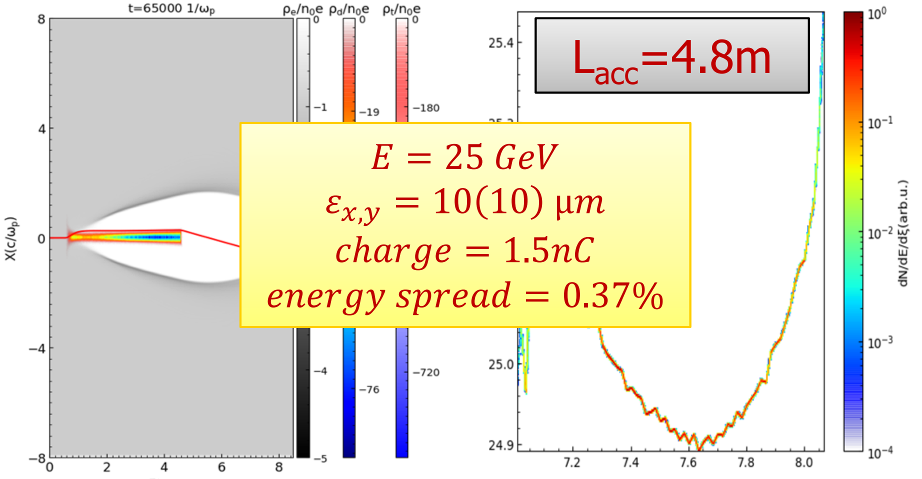


Evaluate the “real” noise level

Initial noise of a collimated beam

- Particle number is N, transverse profile is Gaussian with r.m.s. size σ_r → the jitter of bunch center obeys a Gaussian distribution $N\left(0,\ \sigma_r/\sqrt{N}\right)$
- For PIC simulation, number of macro particle is much less than practical particle number, so the initial noise level is different in magnitudes.
- Let asymmetric rate $n = \sqrt{N_{macro}/N_{practical}}$. The noise level in a real case is similar with the case that $(1-n)$ portion of driver particles are symmetrically treated before the simulation
- Take CPI e- PWFA as an example, $n = 2\%$ In such condition, the trailer can’t be accelerated to 30 GeV or 45 GeV due to hosing instability.
- For the next step, we will lowered the noise level directly in QuickPIC code during the loading beam process

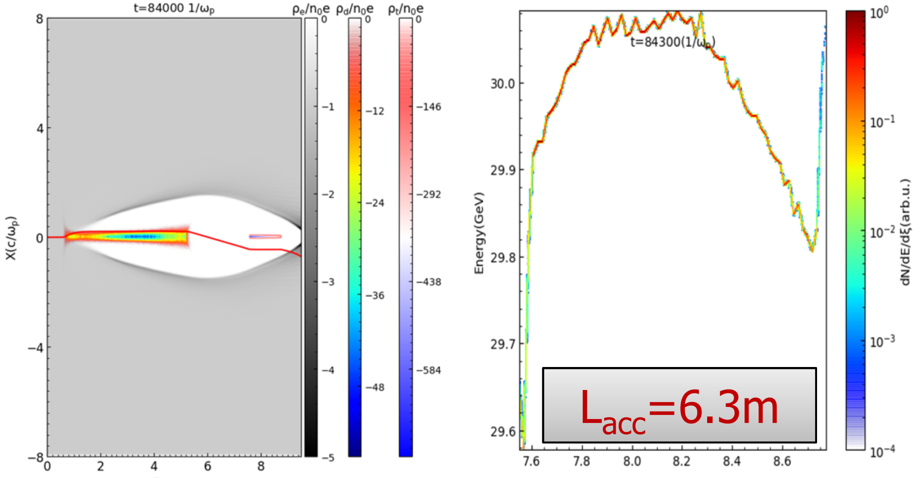
Hosing instability for TR= 1.5 & 2



L_{acc}=4.8m

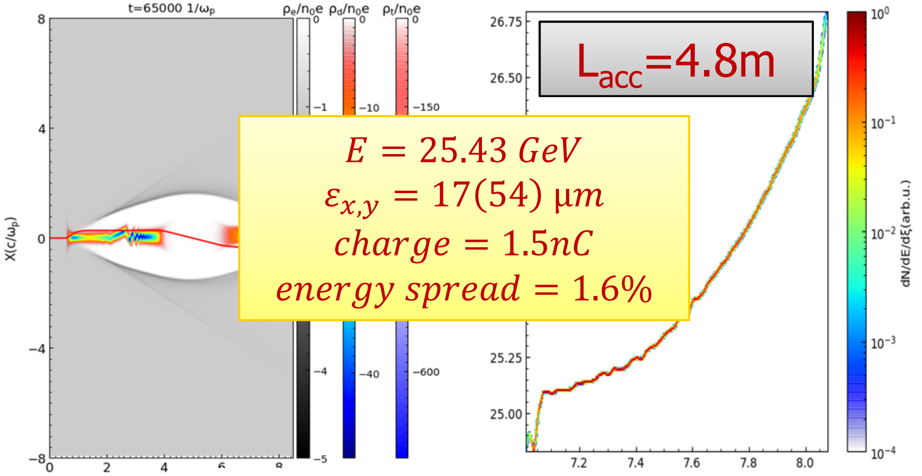
$E = 25\ GeV$
$\varepsilon_{x,y} = 10(10)\ \mu m$
$charge = 1.5nC$
$energy\ spread = 0.37\%$

TR=1.5, Ideal case



L_{acc}=6.3m

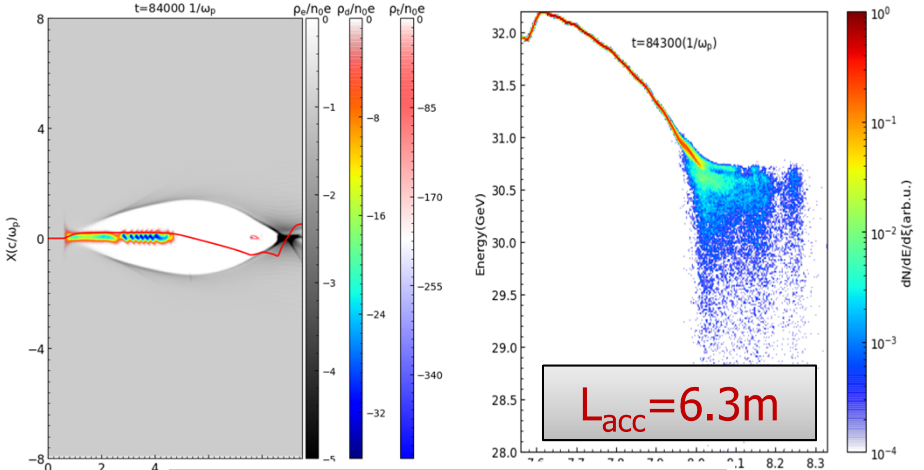
TR=2.0, Ideal case



L_{acc}=4.8m

$E = 25.43\ GeV$
$\varepsilon_{x,y} = 17(54)\ \mu m$
$charge = 1.5nC$
$energy\ spread = 1.6\%$

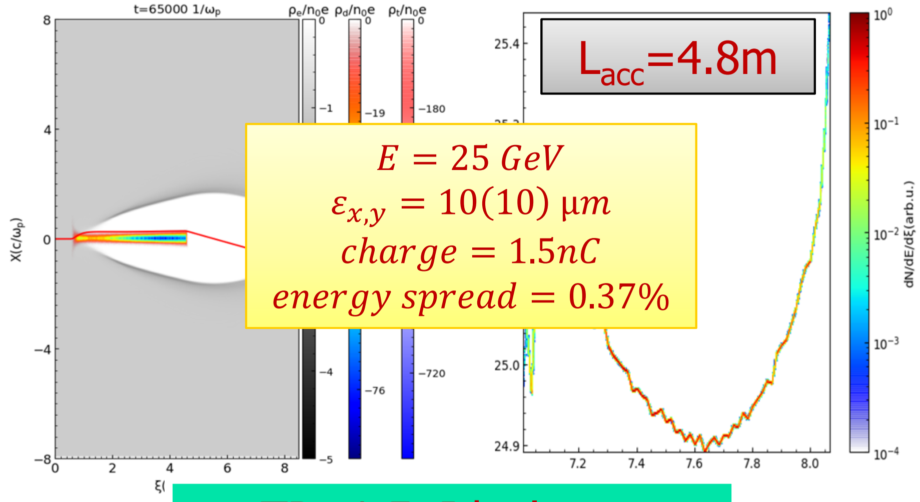
TR=1.5, n=2%



L_{acc}=6.3m

TR=2.0, n=2%

Hosing instability for TR= 1.5 & 2



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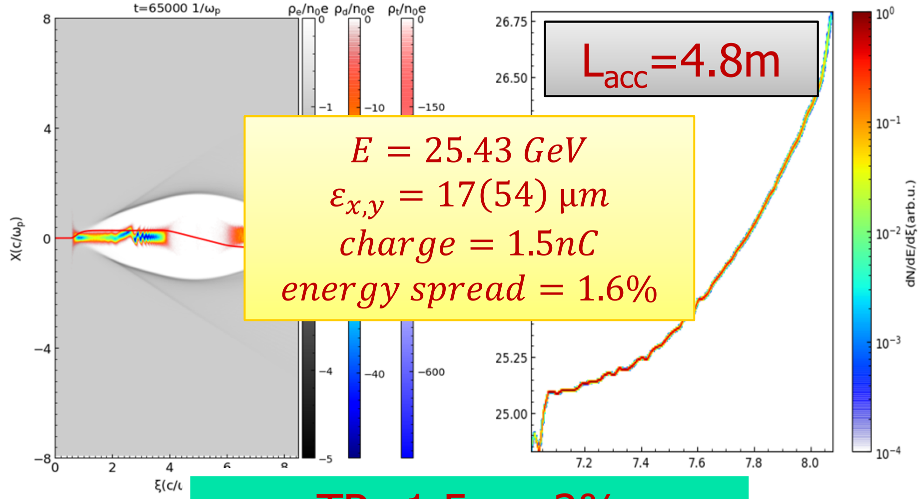
TR=1.5, Ideal case



L_{acc}=4.8m

$E = 25.43\ GeV$
$\varepsilon_{x,y} = 17(54)\ \mu m$
$charge = 1.5nC$
$energy\ spread = 1.6\%$

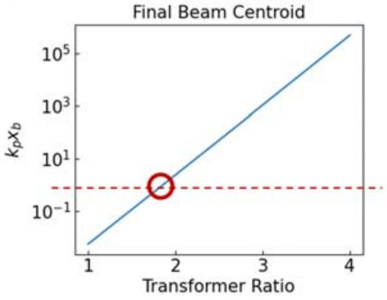
TR=1.5, n=2%

- 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.

Error tolerance for TR=1.5/2/3.5

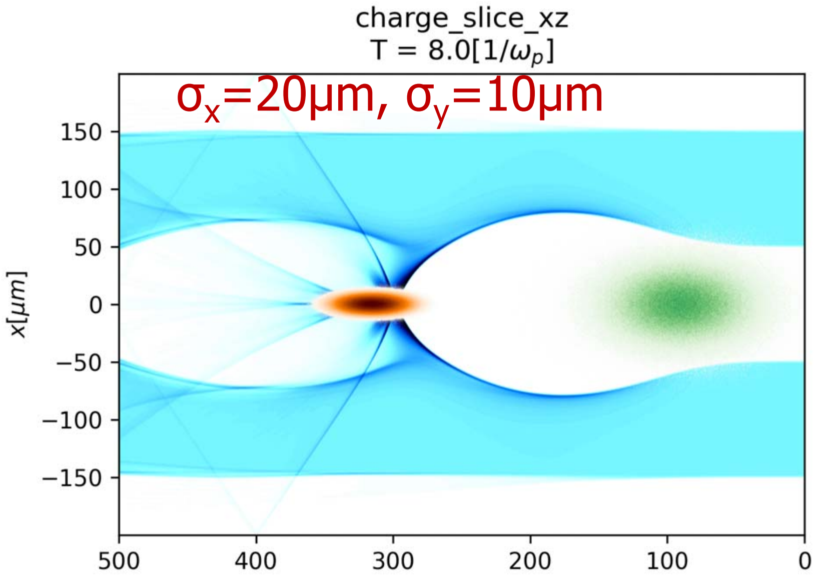
	X, Y offset μm	Z offset μm
TR=3.55, ideal	(-2.4, 2.4)	(-1, 0.25)
TR=2, ideal	(-13.5, 13.5)	(-3.4, 3.4)
TR=1.5, ideal	(-40, 40)	(-3.7, 3.6)
TR=1.5, n=2%	(-3, 3)	(-4, 1)

Requirement:

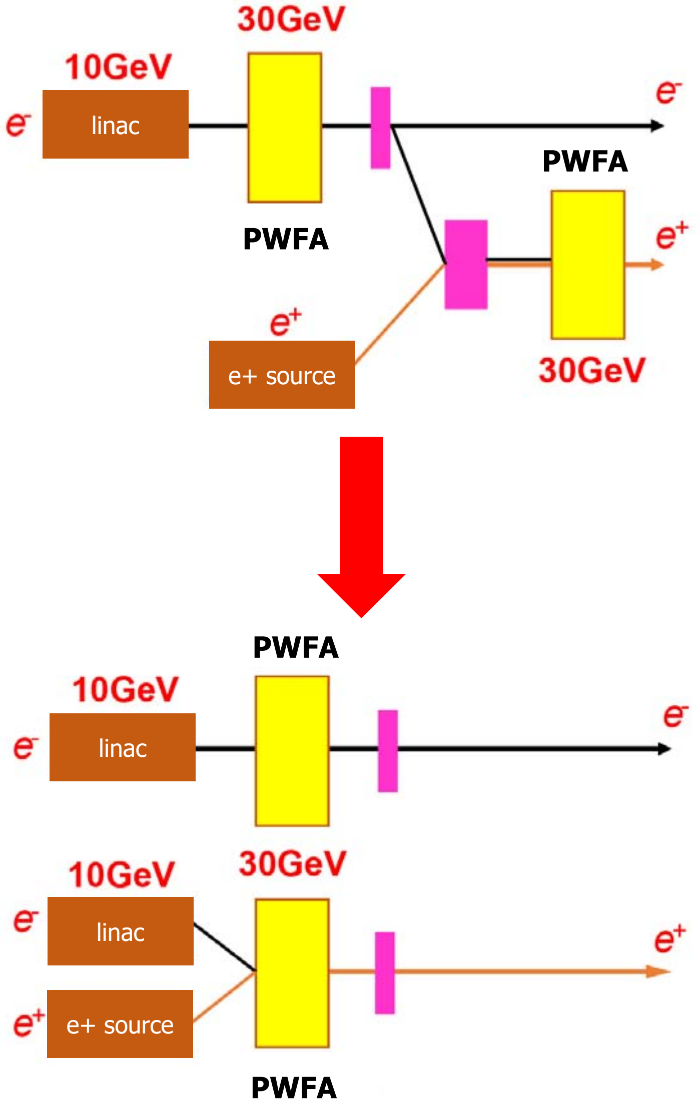
- Q (25GeV±2%) $\geq$ 1 nC
- $\varepsilon_{x,y} \leq 1$ nm
- For TR=1.5 & n=2% case, the initial bunch charge with ±2% energy spread is 1.04 nC, which is close to the limit. So the error tolerance analysis need further discussion

- **According to the theoretical and simulation analysis, TR=1.5 seems good enough to fulfill the booster requirement, even without extra damping methods.**
- **CPI may save at least 200-300 million CNY. If the linac energy can be increased to 12 GeV (~ +100 m CNY), ~ 1 billion CNY may be saved with TR=1.5 scheme.**
- **TR=2.0 or higher scheme is still under consideration. It could be OK if the damping methods such as ion motion, BNS damping, etc. are taken into account.**

e+ acceleration → asymmetry driver



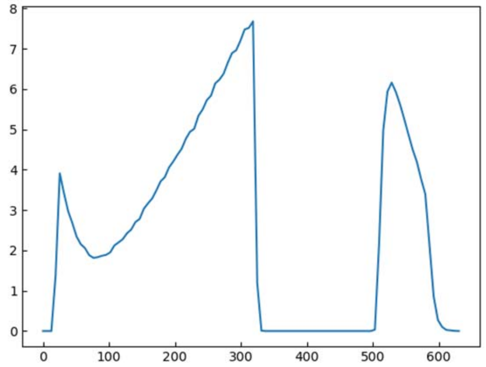
S. Y. Zhou, W. Lu, *PRL* 127, 174801 (2021), Editor Suggestion

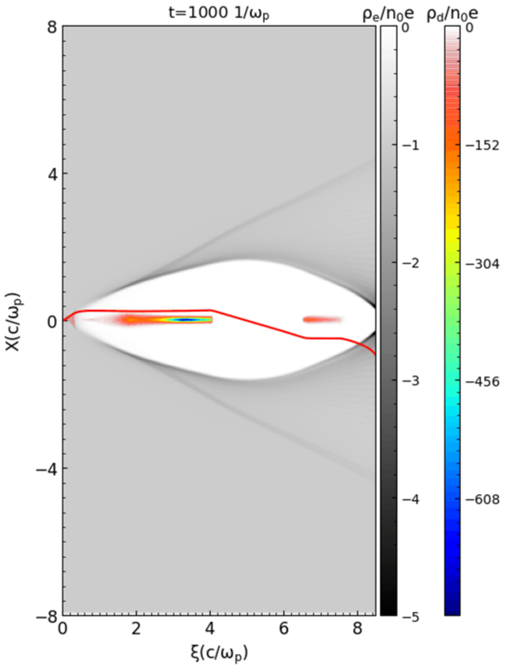


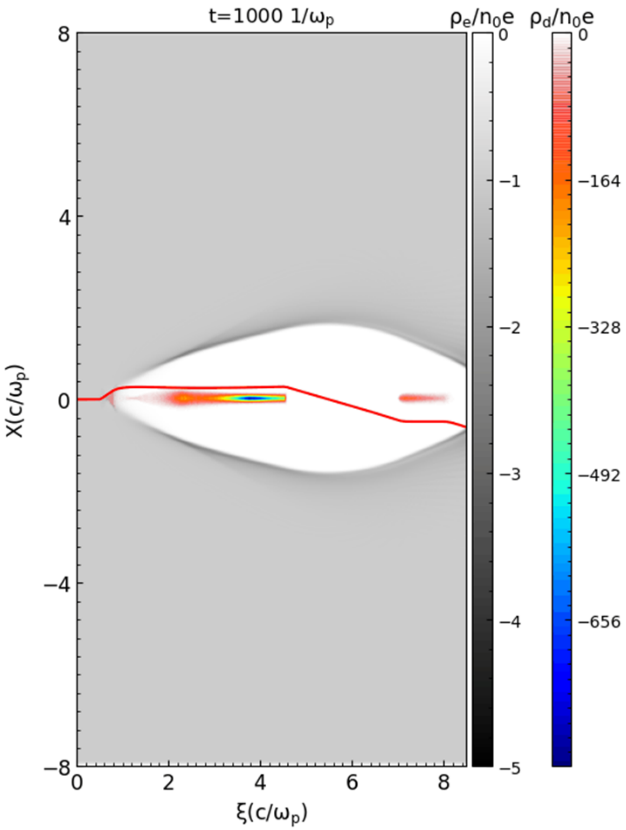
Further optimization:

- Increase the efficiency from 30% to 50%
- Optimize energy spread (shaped trailer / APD)
- Fix the e+ PWFA parameters before 2022.10
- New acceleration scheme (TR ~ 2)

Start-to-end simulation→ wo matching





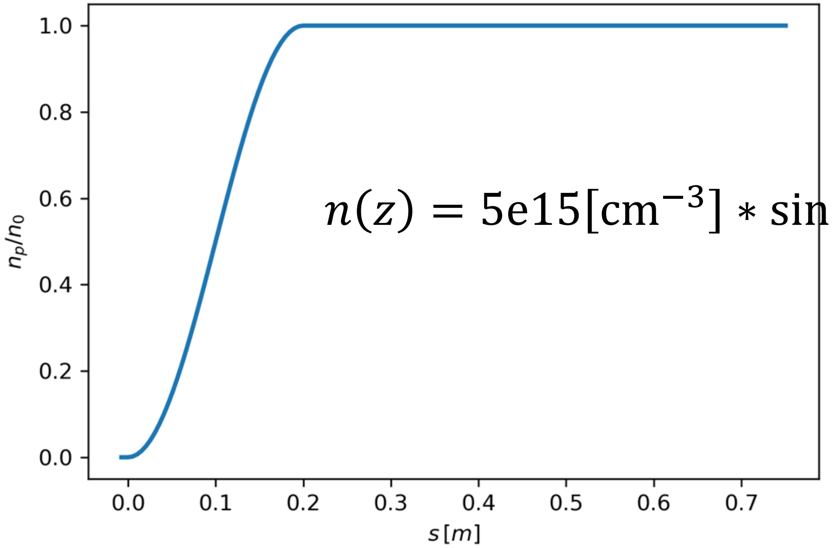


- **Driver:**
  - **<x>=11.63 μm → 3.64 μm**
  - **<y>=20.13 μm → 3.64 μm**
- **Trailer:**
  - **<x>=20.52 μm → 8.65 μm**
  - **<y>=35.06 μm → 8.65 μm**
- **Total particle # ~ 1e6**
- **Real particle # ~ 2.5e10**
- **n=2%, even without plasma matching section:**
  - **<E>=26.9 GeV**
  - **rms ΔE/E =1.46%**
  - **Q=1.27 nC**
- **Non-ideal energy chirper**

Upramp plasma matching section

CPI needs μm-level beams

- Well designed longitudinal plasma density distribution may help focusing the e- / e+ beams without emittance increase.
- The plasma sources should have plasma upramp section in real cases
- The final focus design could be much more easier



$$n(z) = 5\text{e}15[\text{cm}^{-3}] * \sin^2(\pi z/20[\text{cm}])$$

Beam parameter	Before plasma	In uniform plasma
α	0.98	-0.02
β [m]	0.091	0.015
ε_n [mm·mrad]	10.038	10.042
σ_r [μm]	6.746	2.723

Y. Zhao, et al., PRAB 23, 011302 (2020).

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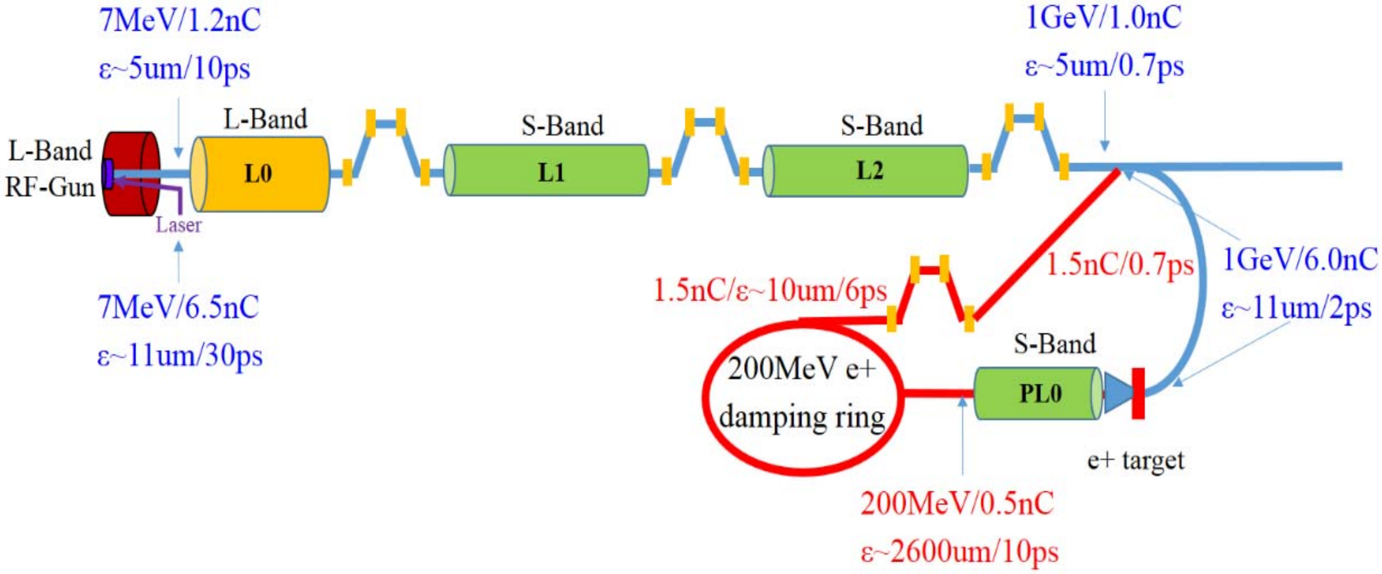
- Key technology for CPI and our road map

Key comments and recommendations

- **Why use 10 GeV beam in CDR instead of using 20 GeV in new baseline?**
  - ✓ **In new baseline, linac = S-band + C-band. Hard for high charge acceleration(≥ 10 nC) → necessary for e+ acc.**
  - ✓ **10 GeV → 25/30 GeV is the most cost-effective way for CPI**
- **The linac optimization for CPI is important and need more optimization**
  - ✓ **Should and will be improved.**
  - ✓ **The linac requirement was changed several times according to CPI design.**
  - ✓ **Will fix the requirement ASAP and finish the start-to-end simulation at the end of this year.**
- **PWFA is not mature enough in technique now and CPI may not catch up with the CEPC TDR/EDR schedule**
  - **Agree with the reviewers' comments.**
  - **CPI will not affect the basic infrastructure a lot → CPI has extra time compared with other hardware system or the whole physics design.**
  - **CPI is an alternative method instead of a baseline design.**

Key comments and recommendations

- ➢ **Continue the excellent work on simulation of the PWFA acceleration process for electrons and the experimental work on plasma dechirping and plasma lenses**
  - ✓ **The plasma dechirper and plasma lens experiments are prepared and will be performed at SXFEL facility in Shanghai this year.**
  - ✓ **Simulation on (active) plasma dechirper is under study.**
- ➢ **Draw up a submission**
  - ✓ **Already accelera**
  - ✓ **Both re**
- ➢ **Continue t facility to t**
  - ➢ **Trying c**
  - ➢ **Prelimi**



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- **Key technology for CPI and our road map**

Key physics and technology for CPI

- Electron Acceleration
  - High transformer Ratio → TR Vs. Hosing instability
  - Efficiency and beam quality preservation
  - Error analysis and instability study
- Positron Acceleration
  - Stable acceleration (different schemes)
  - Energy spread control
  - Efficiency enhancement……
- Conventional Accelerator design and optimization
  - L-band longitudinal shaped Photon-guns (2 beams in 1 gun?)
  - Linac optimization
  - Positron generation and damping ring
- Beam manipulations:
  - Plasma dechirper
  - External injection
  - Staging and cascading ……

Preliminary analysis	Detailed simulation	Experimental test finished
🟦 √		
🟩 √	🟩 √	
🟥 √	🟥 √	🟥 √

Tentative Timetable for CPI R & D

Estimated finish time	Subjects
2022.12	Start-to-end simulation (PWFA & conventional acceleration)
2022.10 (2023.06)	Positron acceleration error analysis (and efficiency optimization)
2022.10	Linac optimization, final focus and e+ beamline design (e-gun excluded)
2023.06	Photon RF gun optimization (including 2 beam in 1 gun design)
2022.12 (2023.06)	5-10m Stable plasma source prototype (with igniting laser)
2022.12	Plasma dechirper experiments for high charge and energy @ SXFEL
2022.10 (2023.12)	Active plasma dechirper design and (experimental test)
2023.12	2 bunch e- PWFA with high efficiency and beam quality (TR≥1) @ SXFEL
2023-2025	Experimental test for e+ PWFA acceleration @ FACET-II
2023.12 (2024-2025)	Cascaded PWFA for CEPC full energy injection, simulation and (experiments)

Thank you!