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

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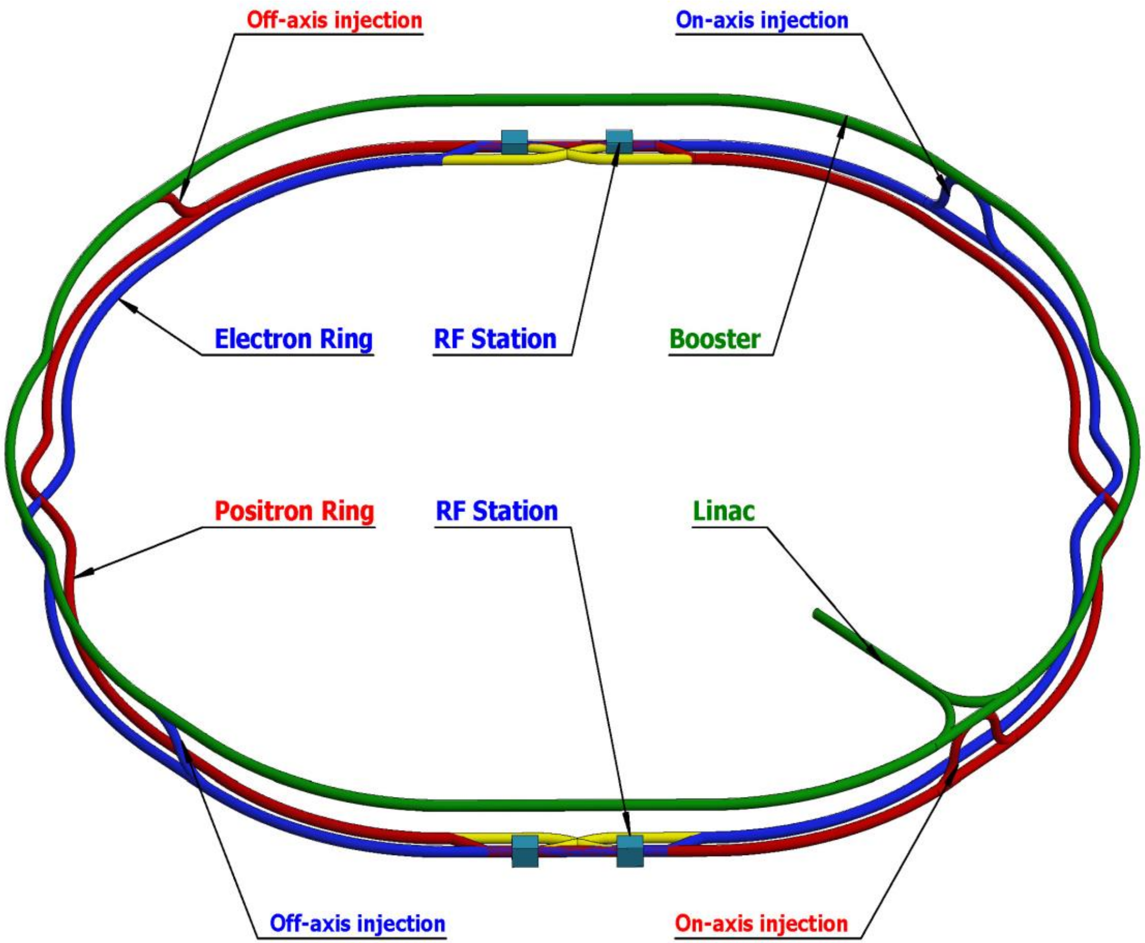
On behalf of the IHEP-THU-BNU AARG team

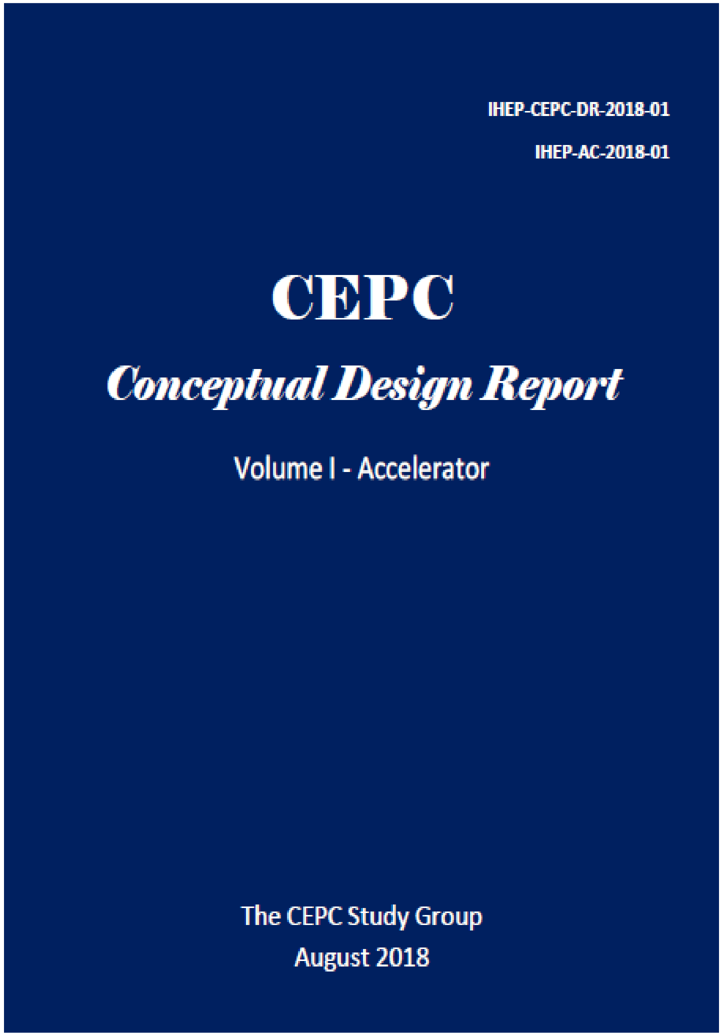
May 12, 2021

Outlines

- Background: CEPC/CEPC plasma injector
- Preliminary design v2
- Current status: Simulations & experiments
- Outlook: Future experiments

Circular Electron Positron Collider





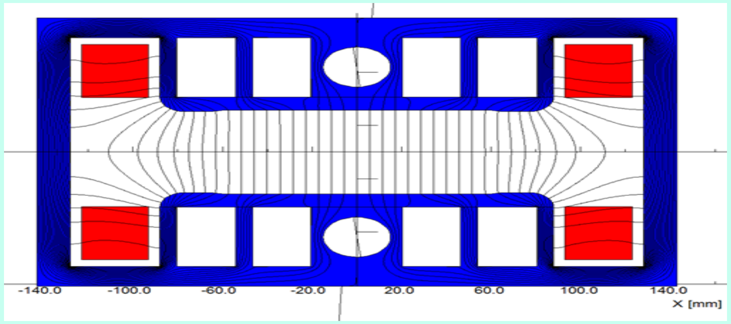
CDR (Acc.) International Review @ 2018.6.28-6.30 & Final Released @ 2018.9.2

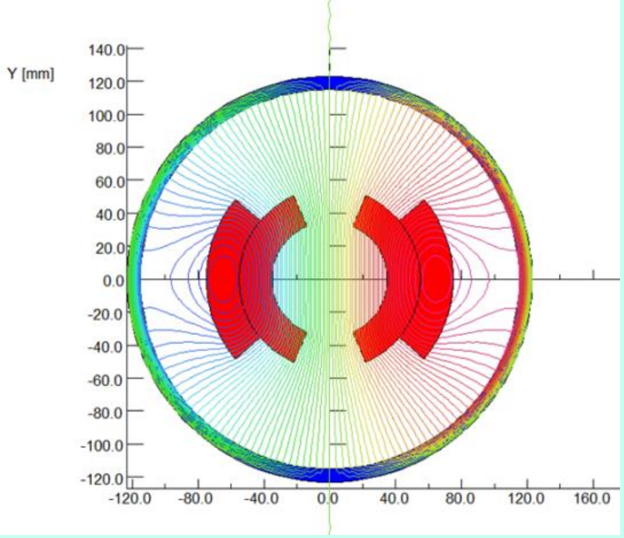
Low field Dipole Problem in Booster

Can we use a 10m scale plasma accelerator to boost the energy of the injector from 10GeV to about 45.5 GeV?

- 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.

(Twice excitation current)



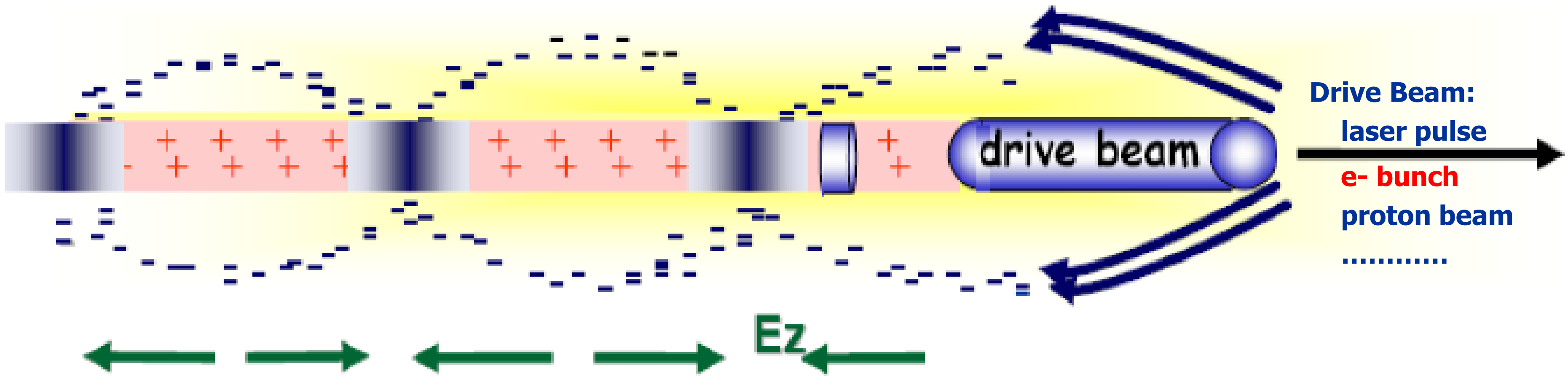


➢ Thinking beyond CDR

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

  - Sextupole coils outside vacuum chamber

Plasma-based wakefield acceleration



Tajima & Dawson, PRL (1979)
Chen et al., PRL (1985)

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0}=-\omega_p^2\frac{n_{\text{beam}}}{n_0}+c^2\nabla^2\frac{a^2}{2}$$

- Plasma wave: electron density perturbation
- Space-charge force of particle beam
- Ponderomotive force (radiation pressure)

$$a=\frac{eA}{mc^2}\propto \lambda I^{1/2}$$

LWFA or PWFA? A simple math problem:

1nC, 100Hz, 10 → 40 GeV: ΔP_{ave} ~ 3kW

Laser → e-: ~1%, 1PW/30fs/10Hz ×1000??

e- driver → e- trailer: 60% per stage!!

Plasma wave excitation, 1~100GeV/m gradient

A young and fast growing group

- **THU team:**
  - **Prof.: W. Lu, J. F. Hua,**
  - **PhD: S. Y. Zhou, S. Liu, B. Peng, Y. P. Wu, Y. Ma, T. L. Zhang, H. Y. Xiao, Z. Song, Y. Fang, F. Yang……**
- **IHEP team:**
  - **Prof.: J. Gao, J. R. Zhang, Y. S. Huang**
  - **Staff: D. Z. Li, M. Zeng, D. Wang, C. Meng, Y. W. Wang, X. H. Cui, G. Shu**
  - **PhD: X. N. Wang, J. Wang**
- **BNU team:**
  - **Prof. W. M. An**

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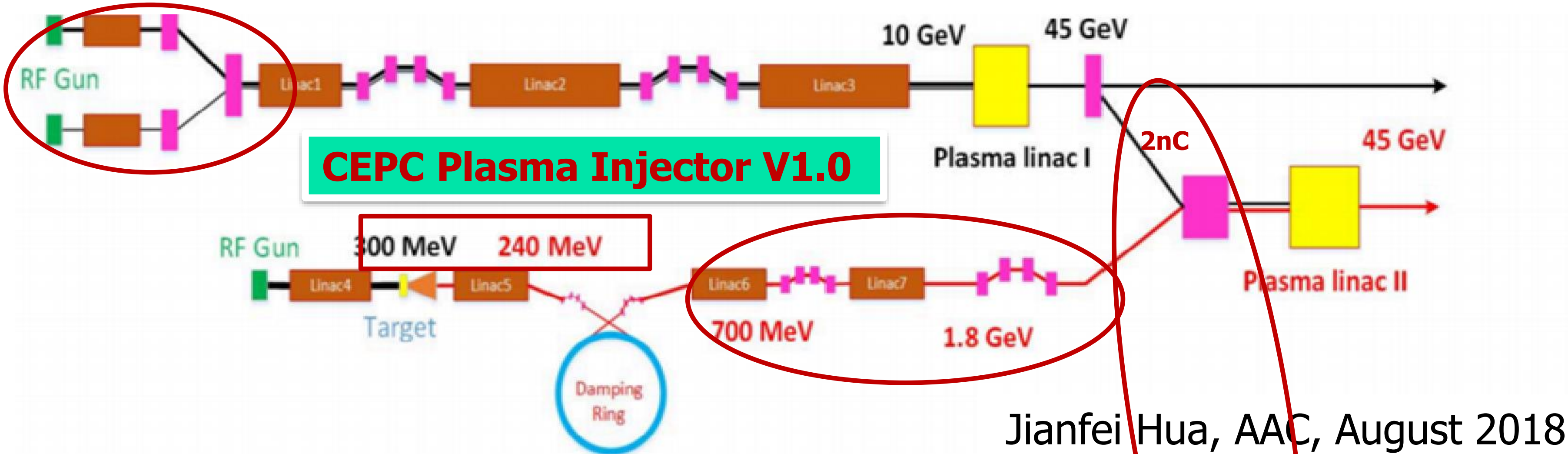
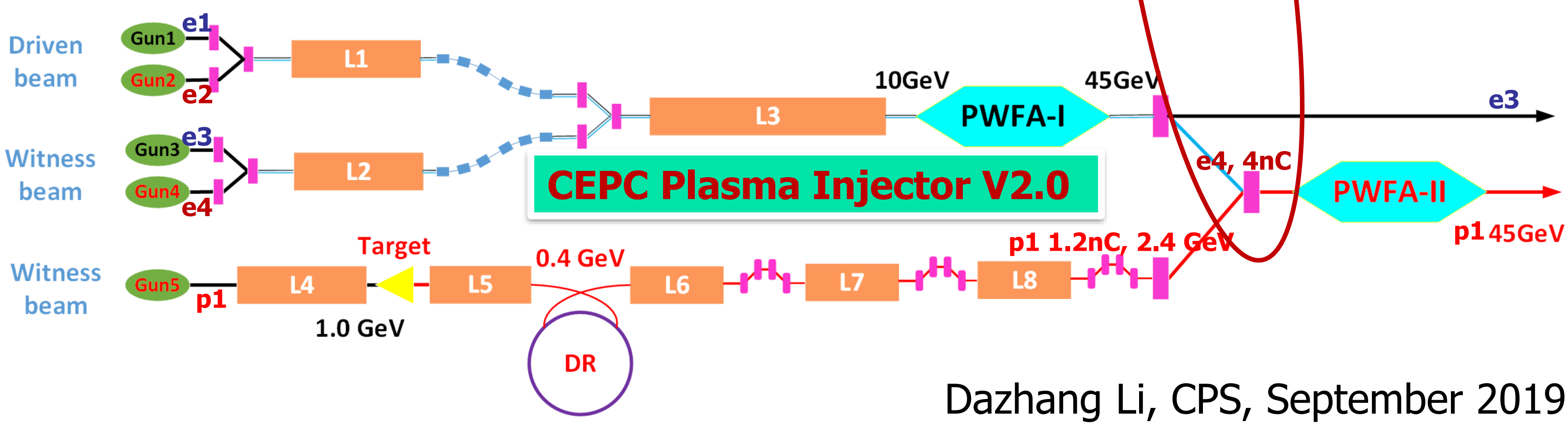
CPI conceptual Design V1.0→V2.0



Jianfei Hua, AAC, August 2018

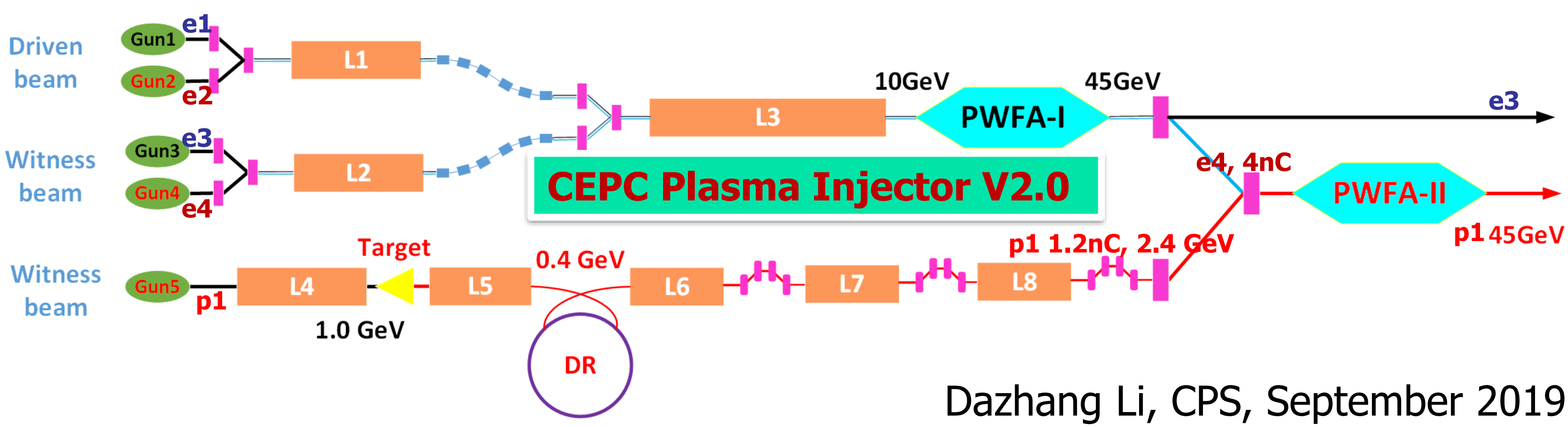


Dazhang Li, CPS, September 2019

Requirement & Key issues of CPI

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

- Electron Acceleration → HTR
- Positron Acceleration → Stable mode
- Conventional Accelerator optimization
- Beam manipulations



Dazhang Li, CPS, September 2019

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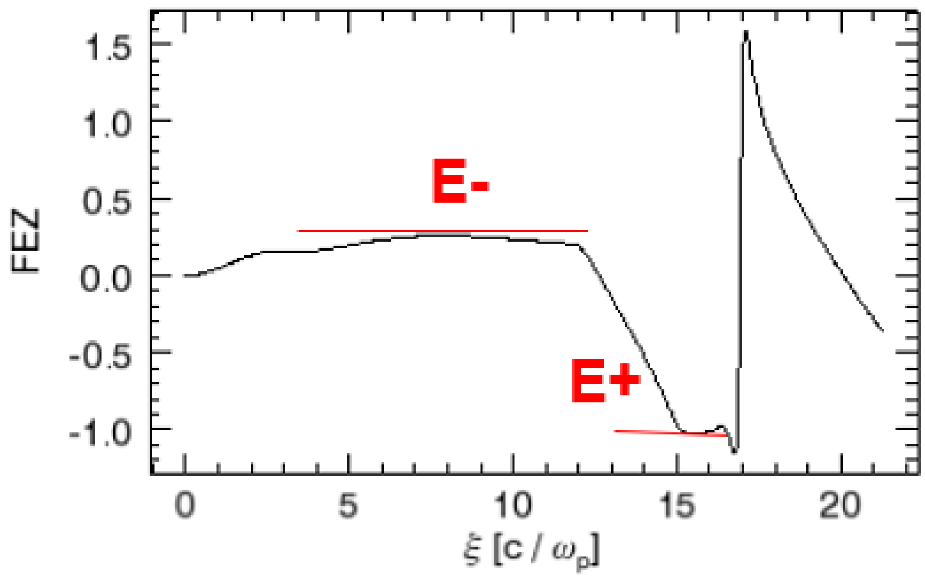
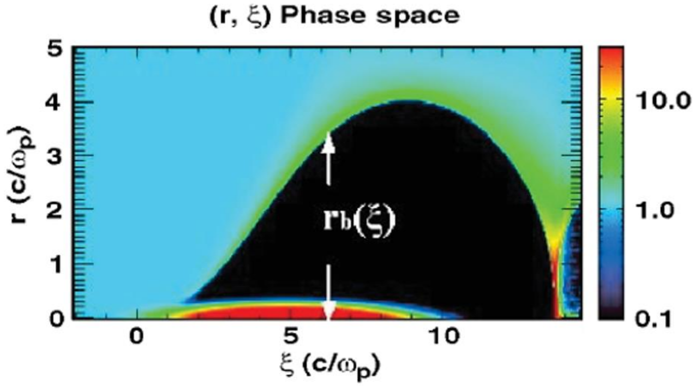
What is High Transformer Ratio?



Nonlinear(Bubble) regime: nb/np>>1 or $\Lambda = n_b/n_p k_p^2 \sigma_r^2 > 1$

HIGH TRANSFORMER RATIO



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

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

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

The equation of boundary: $r_b \frac{d^2 r_b}{d\xi^2} + 2\left[\frac{dr_b}{d\xi}\right]^2 + 1 = \frac{4\lambda(\xi)}{r_b^2}$

$$\psi(\mathbf{r}_\perp, \xi) \approx \frac{r_b^2(\xi)}{4} - \frac{r^2}{4}$$

$$E_z = \frac{\partial}{\partial \xi}\psi(\mathbf{r}_\perp, \xi) \simeq \frac{1}{2} r_b \frac{dr_b}{d\xi} \quad E_\perp = E_r - B_\theta = \frac{r}{2}$$

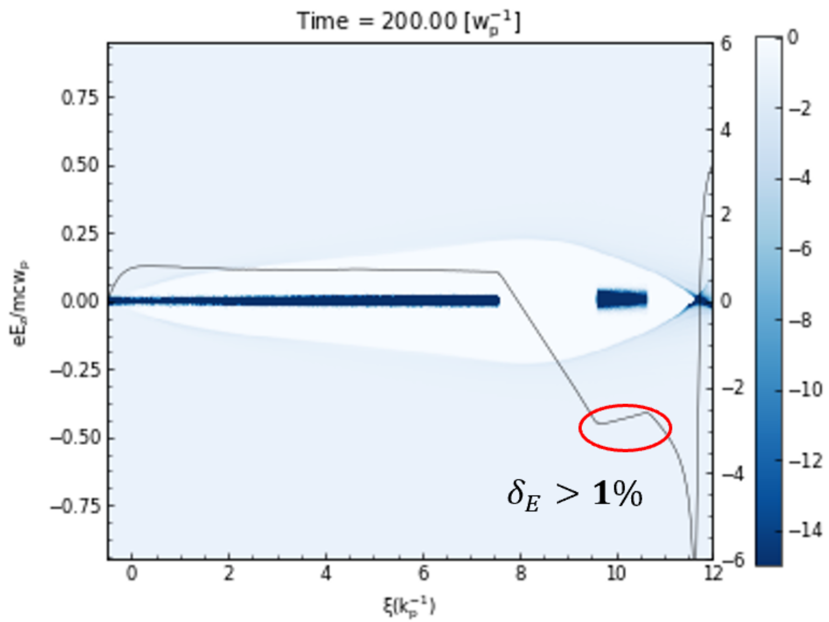
Lu W , Huang C , Zhou M , et al, PRL(2006)

For our case, we need R ≥ (45.5-10)/10=3.55

HTR e- Acceleration—CDR (2018)

beam	Driver	Trailer
Driver energy $E(GeV)$	10	10
Nor. emittance $\epsilon_n(mm\ mrad)$	(head)≤50/≤500	≤100
Length(ps)	2	0.267
Spot size(um)	20	20
Charge(nC)	5.8	1
Beam distance(um)	149	

Density $n_0(cm^{-3})$	0.503×10^{16}
Trailer $E\ (GeV)$	45
TR	3.5
Efficiency (%)	60
Acc. gradient(GV/m)	2.9
Acc. distance (m)	12



1) **Matched beam → Preserve the emittance**

2) **Ez↑→ Trailer's Energy↑ to 45.5GeV**

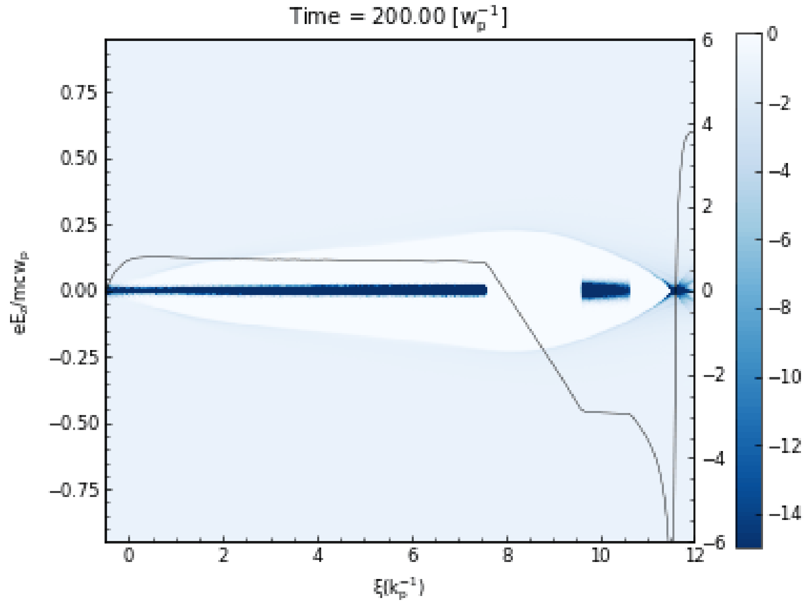
3) **Trailer's Q ↓ → Flatten Ez → Energy spread ↓**

Simulation performed by Dr. S. Y. Zhou and Prof. W. Lu (2018)

HTR e- Acceleration--Optimized

beam	Driver	Trailer
plasma density n_p $(\times 10^{16} cm^{-3})$	0.50334	
Driver energy E (GeV)	10	10
Normalized emittance $\epsilon_n (mm\ mrad)$	50→20	100
Length (um)	600	77
(matched) Spot size(um)	20→3.87	20→8.65
Charge (nC)	5.8	1→0.84
Energy spread δ_E $(\%)$	0	0
Beam distance (um)	149	

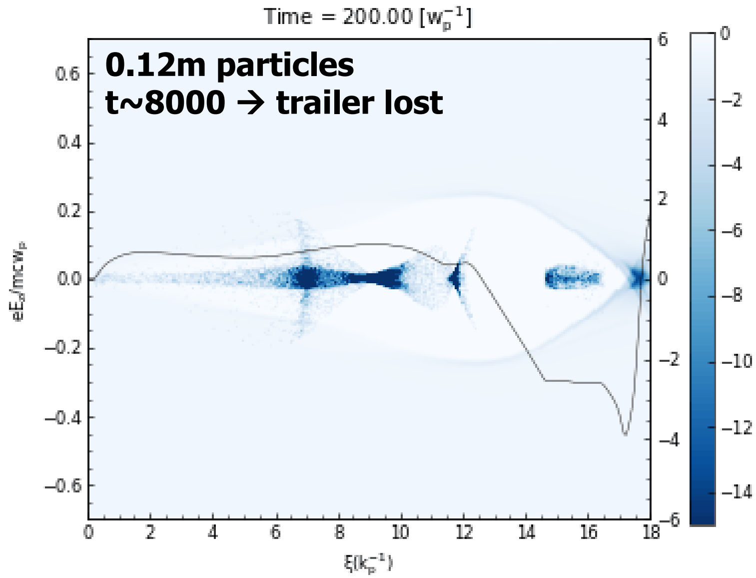
Accelerating distance (m)	10.65
Driver energy $E(GeV)$	1.30
Trailer energy $E(GeV)$	45.5
Normalized emittance $\epsilon_n (mm\ mrad)$	98.44
Charge(nc)	0.84 (0.78)
Energy spread $\delta_E(\%)$	0.56
TR	~ 4
Efficiency (%) (driver → trailer)	59.1

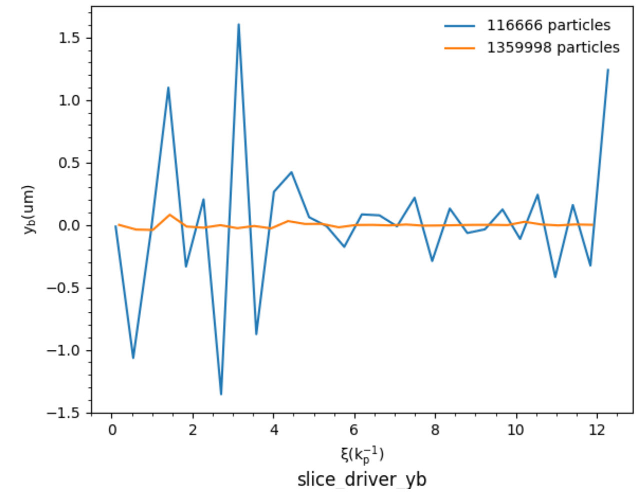


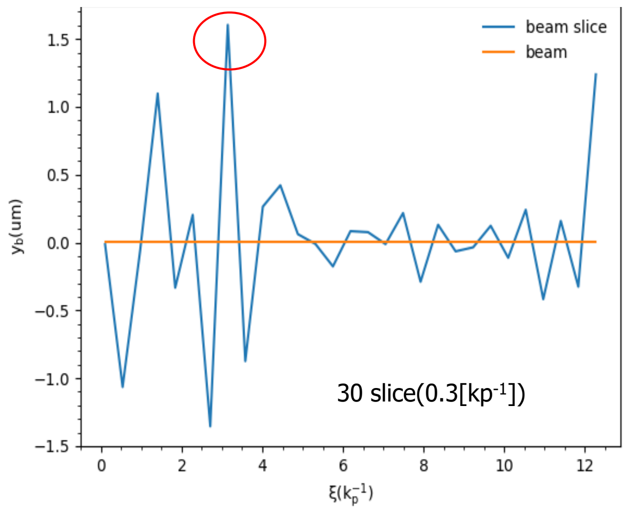
- **10 GeV → 45.5 GeV e- acc. (on paper) work**
- **Much smaller $\sigma_{x,y}$ → Increase Linac difficulty**
- **Trailer's charge close to minimum request**
- **Start-to-end & error analysis studies**

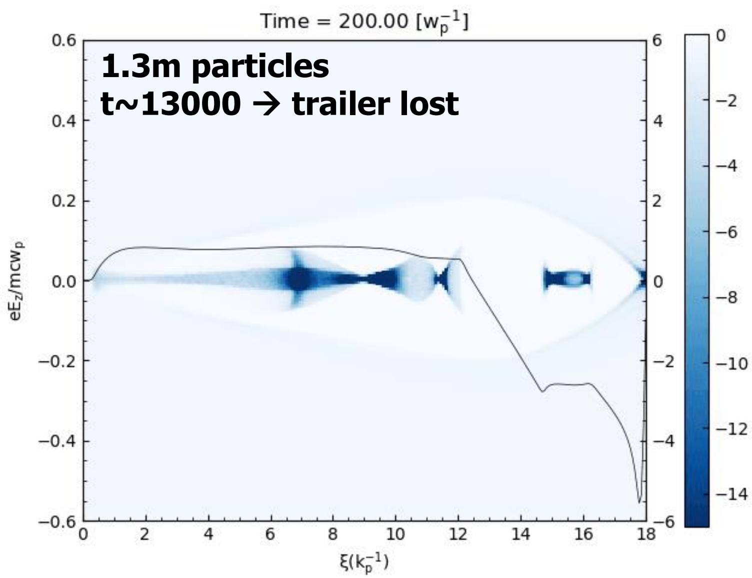
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

Start-to-End simulation Linac → PWFA







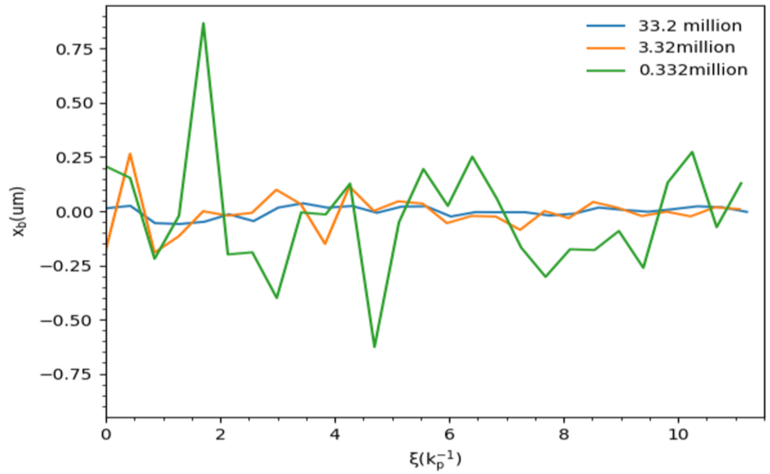


Big slice jitter → Hosing Instability

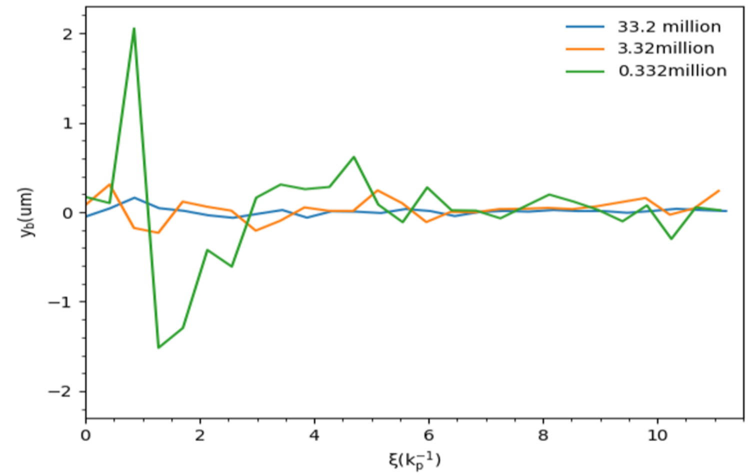
Particle # ↑→ Slice jitter↓ → Hosing ↓

Particle # dependent slice jitter

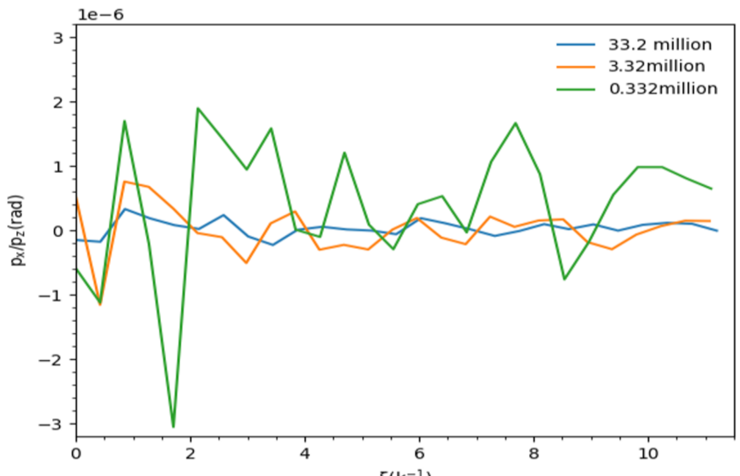
For simple estimation, slice jitter scales as $N^{-1/2}$, but more complicated in a real case



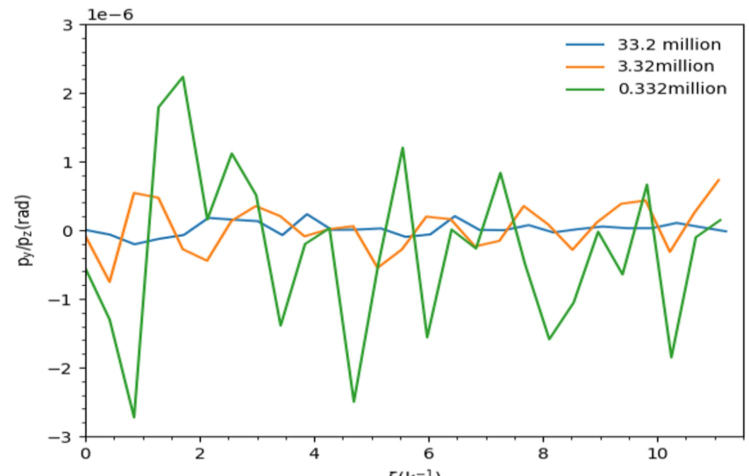
slice_driver_xb



slice_driver_yb



slice_driver_px/pz



slice_driver_py/pz

Single parameter error analysis

Perturbation		Limitation	limiting factor
beam charge	Driver	[-1%, 0.8%]	E_t δ_E
	Trailer	[-0.24%, 2%]	E_t
beam length	Driver	±1%	E_t
	Trailer	±5%	E_t
initial energy	driver	[-1%, 0.38%]	E_t
	trailer	[-1.75%, 0.37%]	E_t
initial energy spread		3.9%	E_t δ_E
Spot size	driver	[-40%, 2%]	E_t
	trailer	[8%, 8%]	E_t

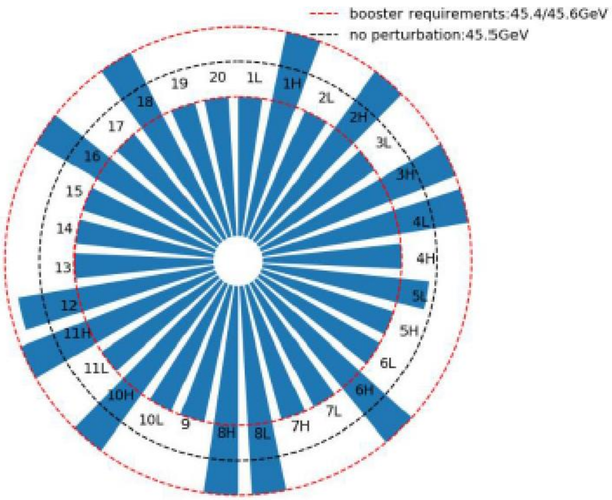
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

Error analysis based on ideal beams

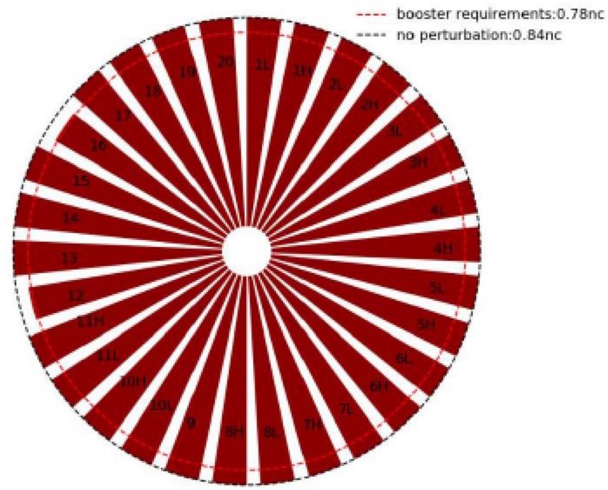
Perturbation			Limitation	limiting factor	Linac simu. data
Centroid offset	Transverse position		±2.4um	Q_t ε_N	Same level
	Transverse velocity	Driver	On going	E_t	35nrad/69nrad
		Trailer		E_t	
Slice jitter	Transverse position	Driver	On going	E_t	Need more studies
		Trailer	±3.7um	E_t	
Beam distance			[-1um, 0.25um]	E_t	~3um (10fs)
Plasma density			±0.3%	E_t	

Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

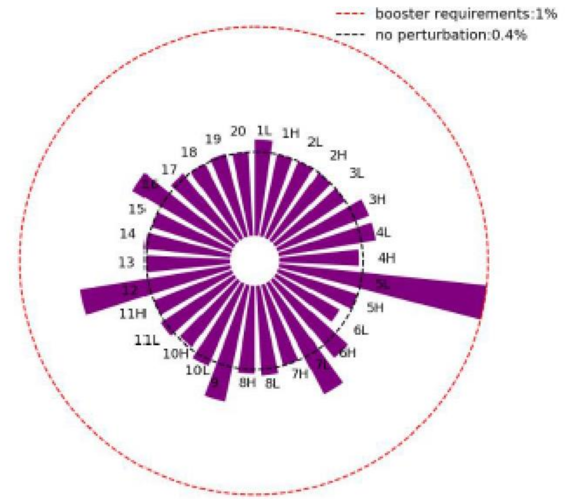
Overall Error Analysis Results



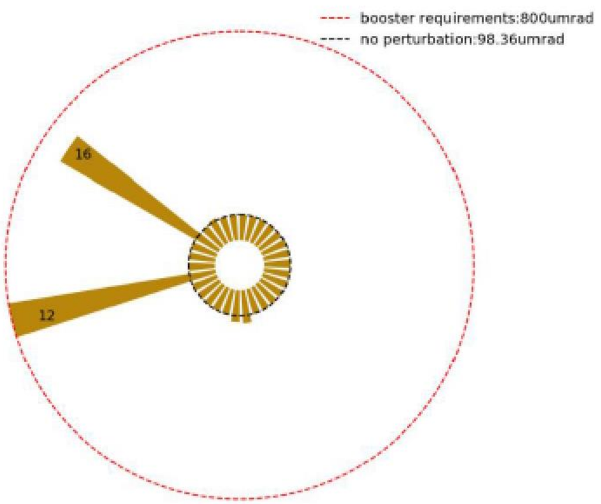
The sensitivity of trailer energy to perturbations



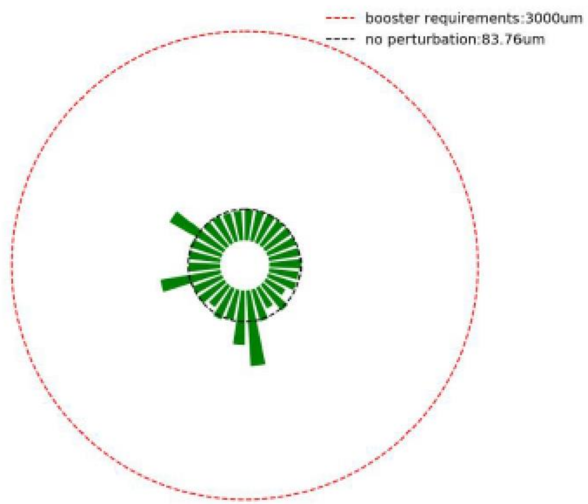
The sensitivity of trailer charge to perturbations



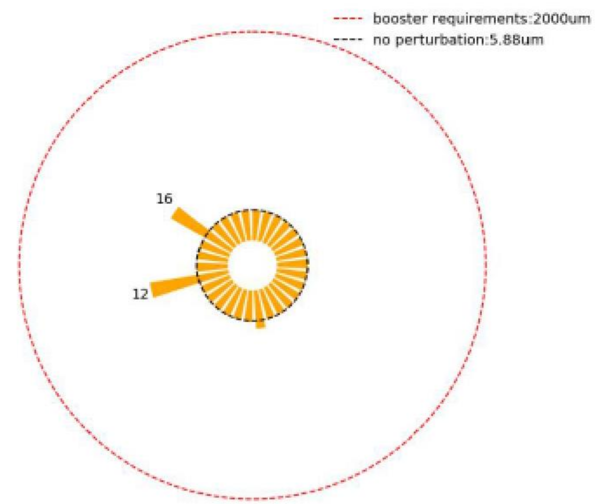
The sensitivity of trailer energy spread to perturbations



The sensitivity of trailer emittance to perturbations



The sensitivity of trailer length to perturbations



The sensitivity of trailer RMS spot size to perturbations

How to improve error tolerances?

1) Better understanding the hosing instability

2) Lower TR / shorter drive beam

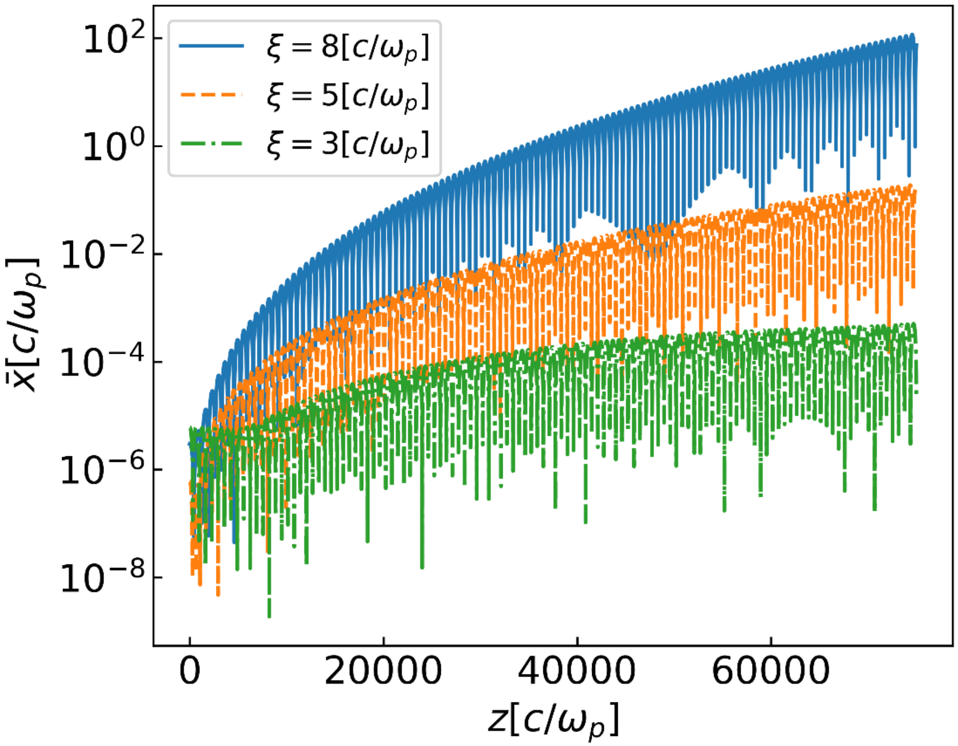
3) Lower plasma density for larger scale

$$\partial_s^2 x_b + k_\beta^2 x_b = k_\beta^2 x_c,$$

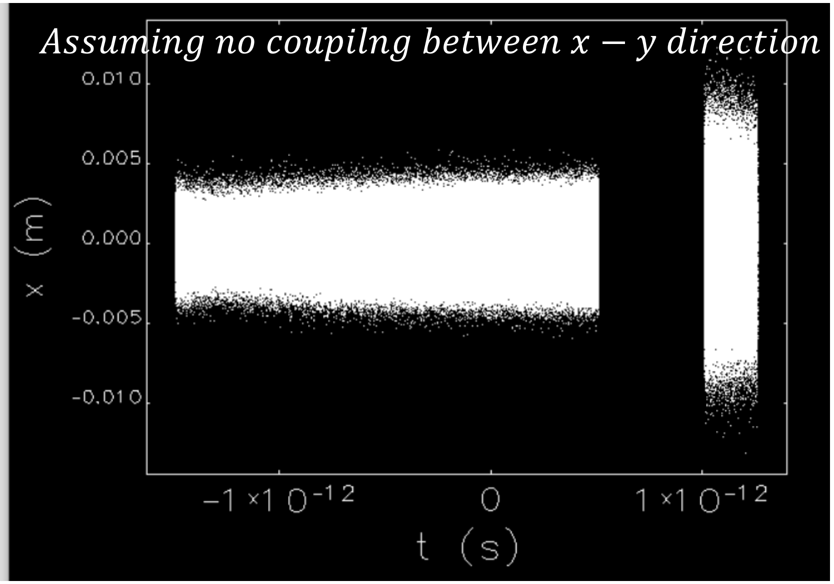
$$x_c'' + c_r c_\psi \omega_0^2 x_c = c_r c_\psi \omega_0^2 x_b.$$

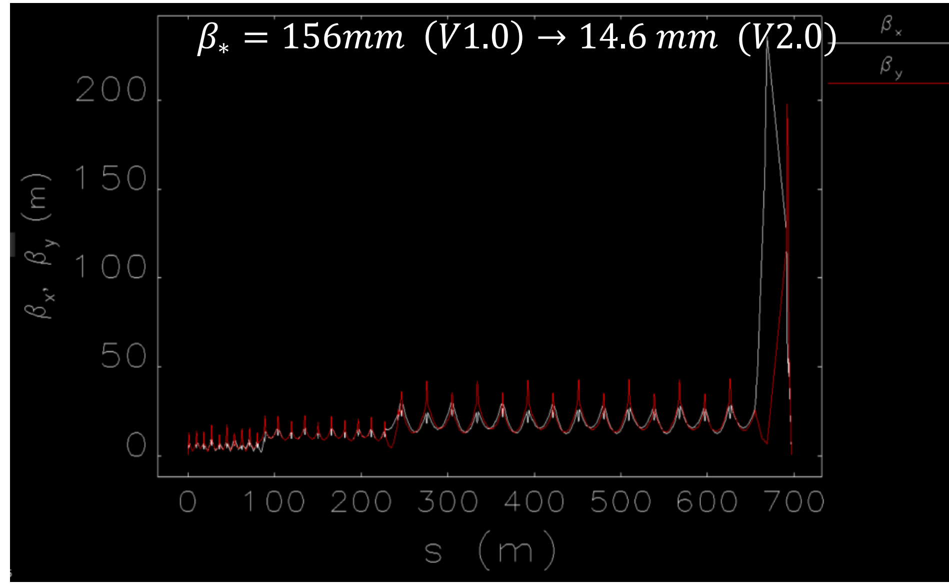
$$c_r \equiv n_b R_b^2 / r_0^2 = r_{\rm neu}^2 / r_0^2$$

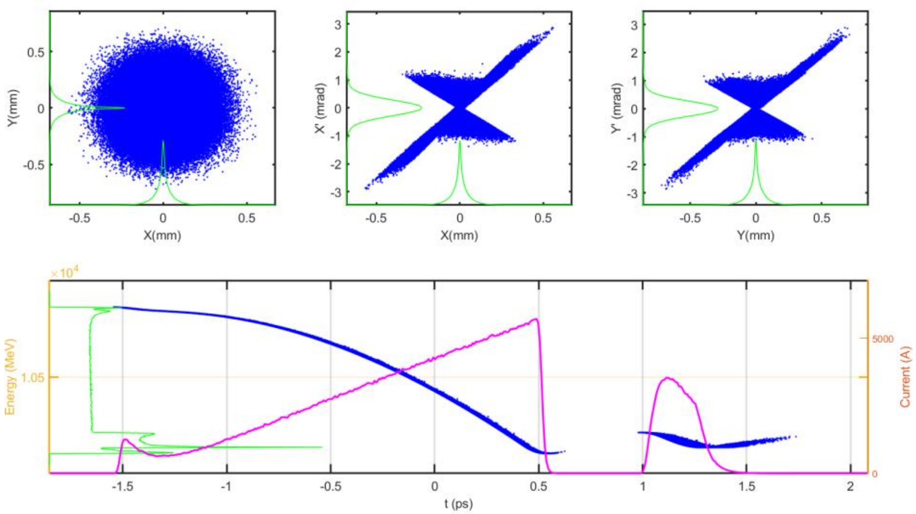
$$c_\psi \equiv 1/(1 + \psi_0)$$



Linac optimization for ideal beams







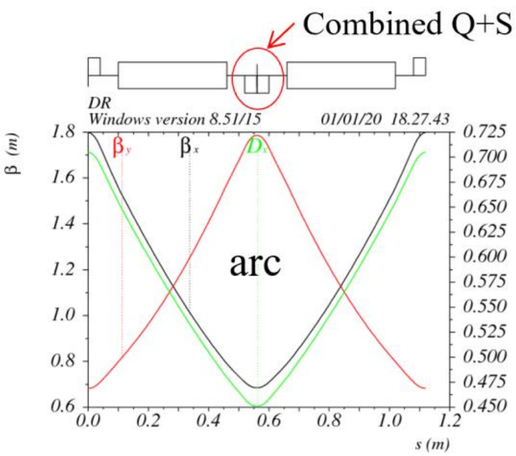
L-band photocathode rf gun under design.

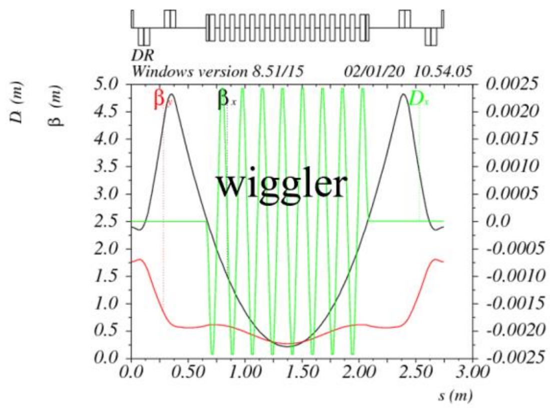
Finished the preliminary linac design and the end-to-end simulation (e- gun → FFS). Beam distribution improved but can not meet the requirements yet.

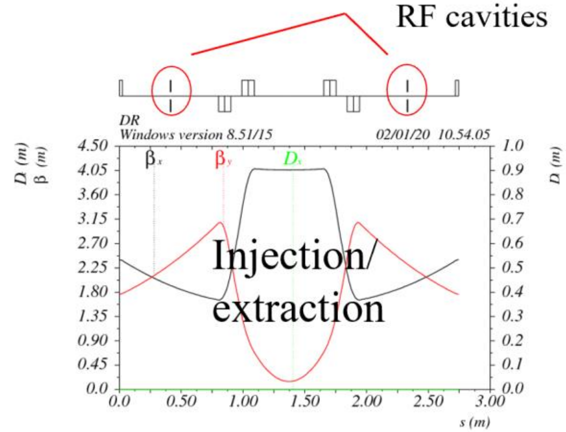
NEED MORE OPTIMIZATIONS

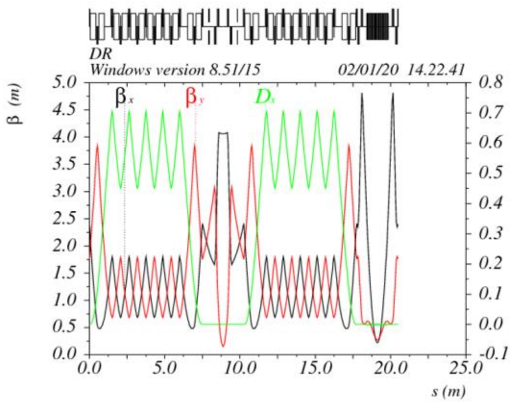
By Dr. Cai Meng rom IHEP (2020)

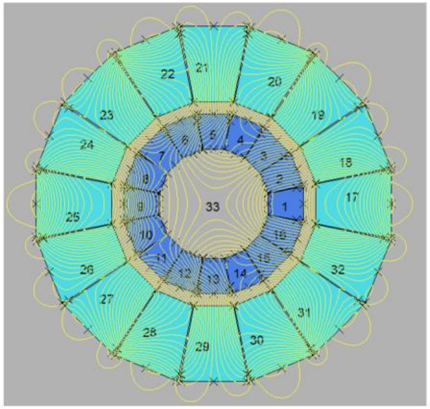
Damping Ring Optics Design V3.0



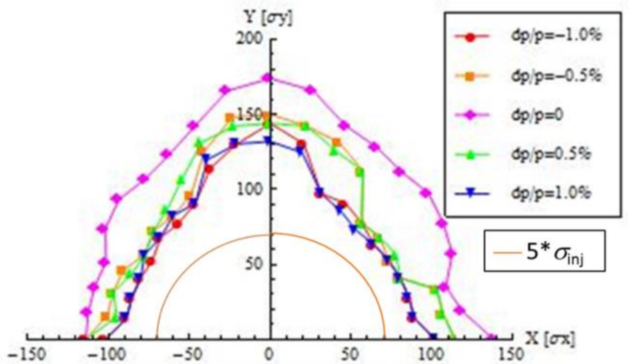








Dynamic Aperture



$\nu_x / \nu_y = 3.16/3.21$

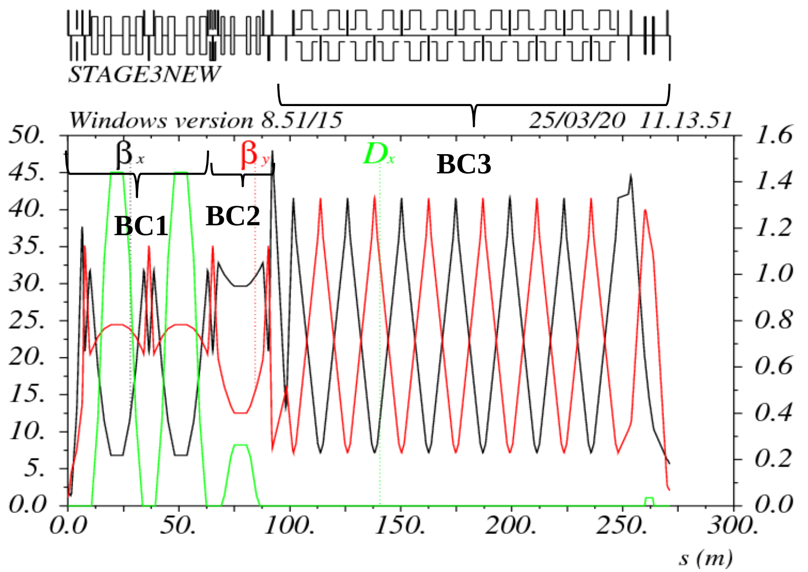
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

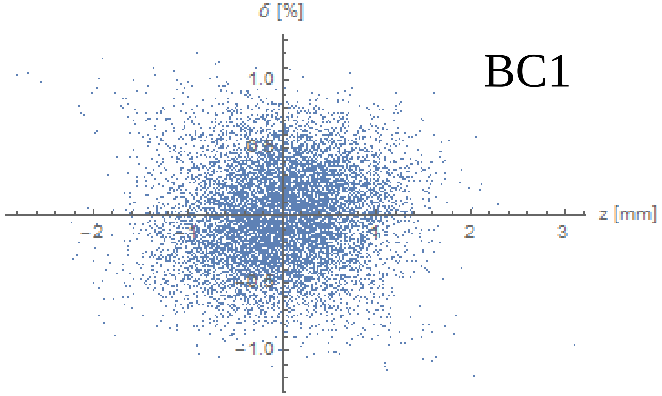
By Dr. Dou Wang and Dr. Cai Meng from IHEP (2020)

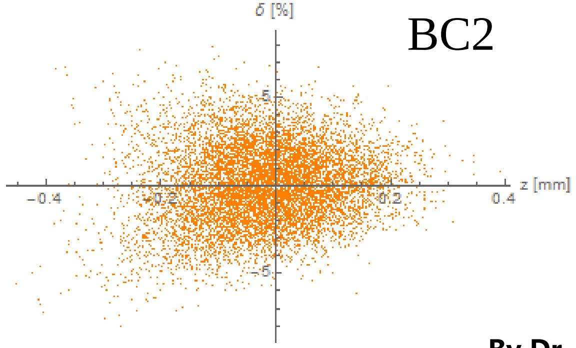
3-Stage Bunch Compressor

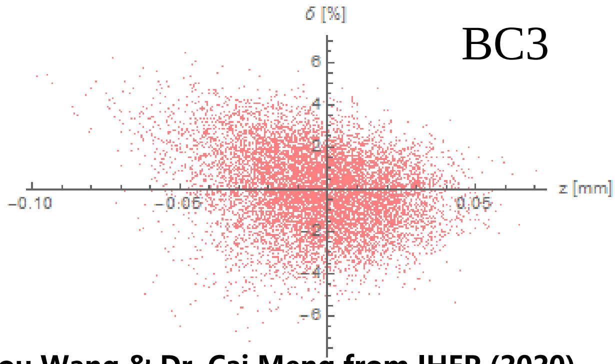
	BCI	BCII	BCIII
Initial energy (MeV)	400	400.1	405
δinj (%)	0.05	0.367	2.17
Initial σz (mm)	4.4	600	100
f_{RF} (GHz)	2.860	5.712	5.712
Voltage(GV)	0.0056	0.12	4.18
Gradient (MV/m)	20	40	40
L (m)	0.28	3	104
ϕ_{RF} (degree)	89	88	61.5
R_{56} (mm)	1200	27.6	5.5
Final energy(MeV)	400.1	405	2400
δext (%)	0.367	2.17	1.83
final σz (um)	600	100	20

- Energy: 400MeV → 2.4 GeV
- Bunch length: 4.4mm → 20um
- Energy spread: 0.054% → 1.8%







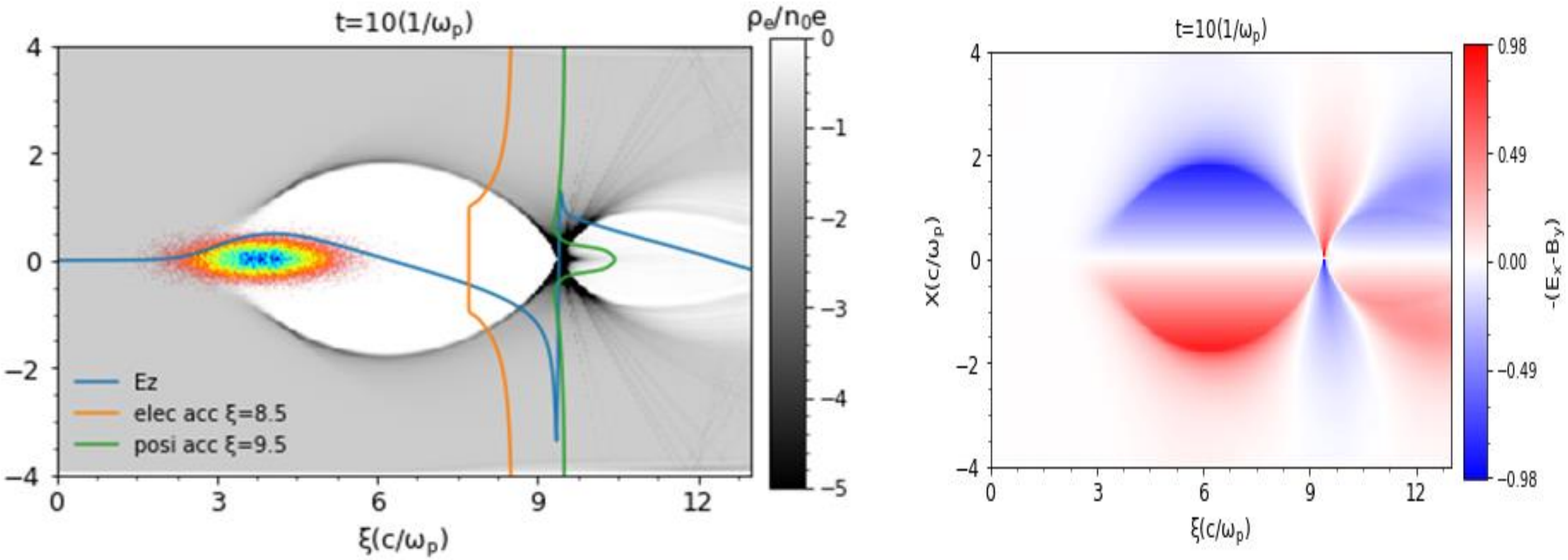


By Dr. Dou Wang & Dr. Cai Meng from IHEP (2020)

Basic ideas for improving e+ acc.

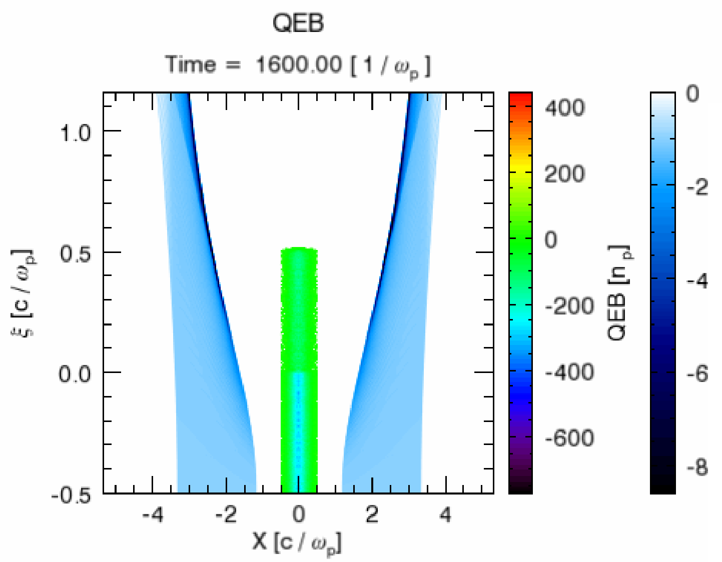
A "perfect" wakefield means:

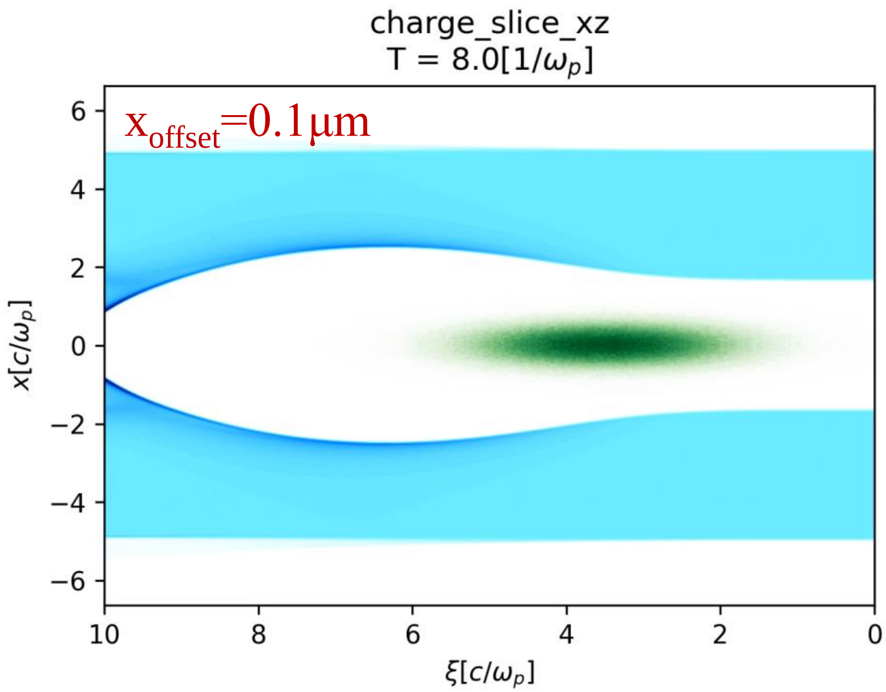
- **Flat longitudinal wakefield, particles at different position experience same Ez**
- **Transverse wakefield can provide focusing forces to the accelerated particles**



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

Baseline method → not very practical

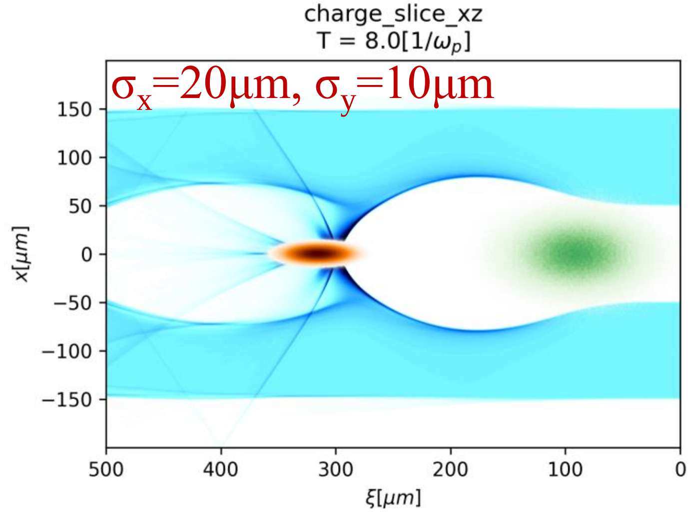


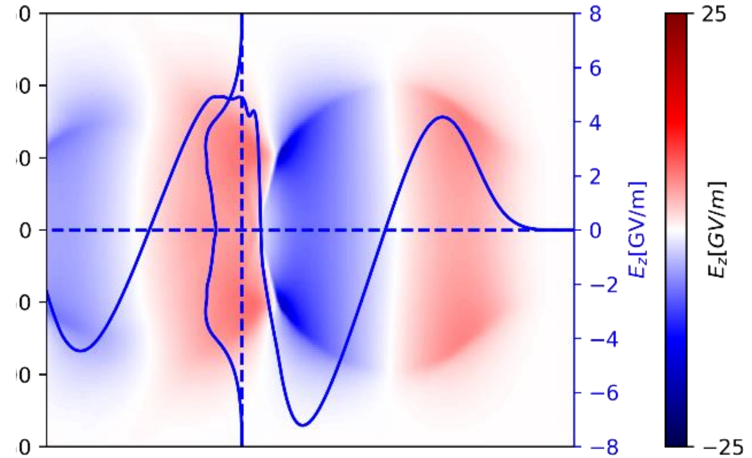


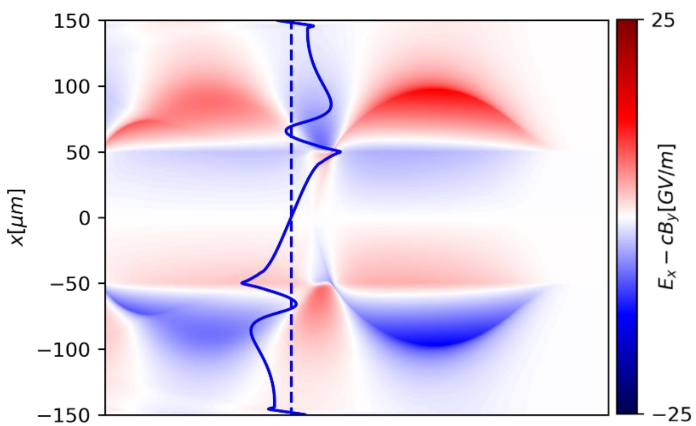
- **High efficiency 60%**
- **Low energy spread ~0.5%**
- **Small emittance growth**
- **Need e- driver, e+ trailer and plasma channel coaxial, not very practical**

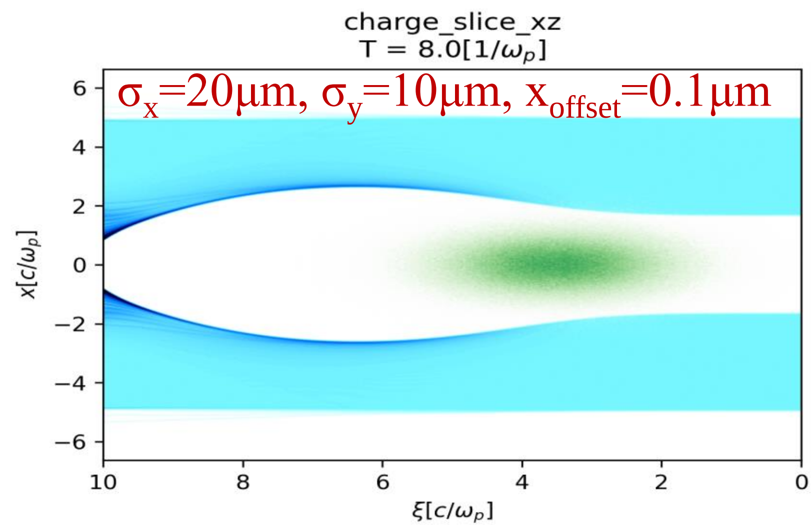
Simulation performed by THU team in 2018, based on the hollow channel idea *[S. Gessner et al., Nat. Commun. 7, 11785 (2016)]*

Modified design → asymmetry driver



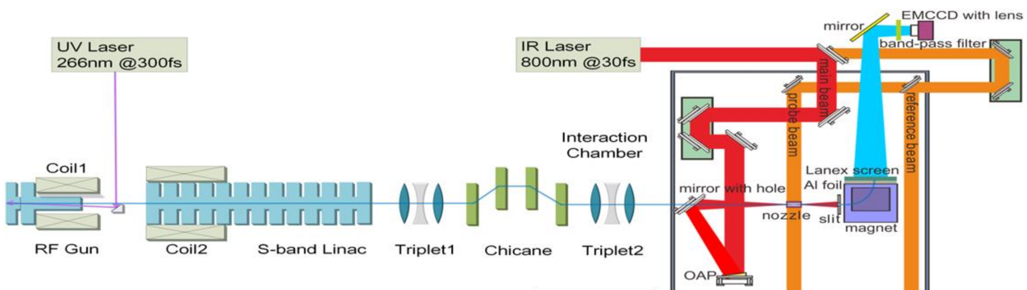






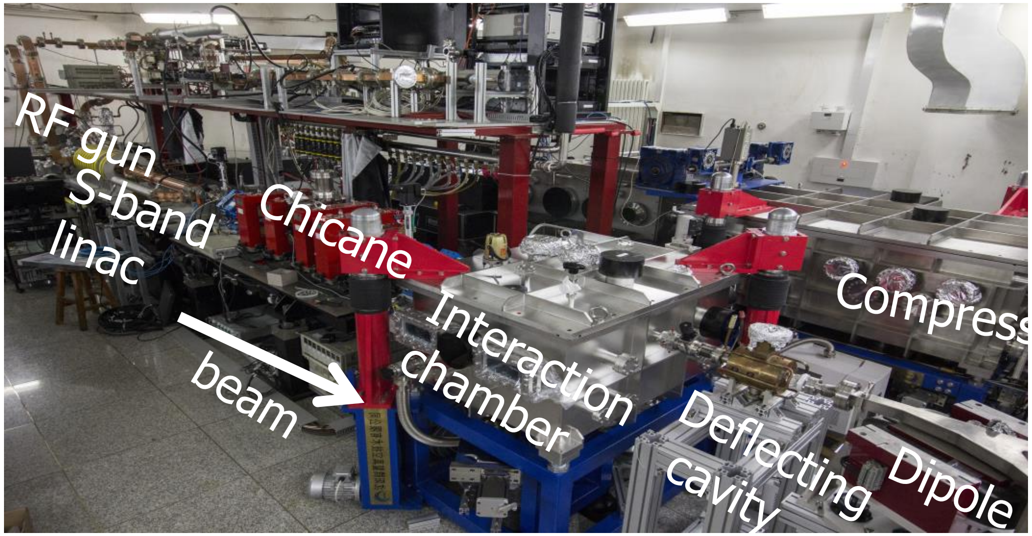
S. Y. Zhou, W. Lu, et al., arXiv: 2012.06095v1, Submitted to PRL (2020.12)

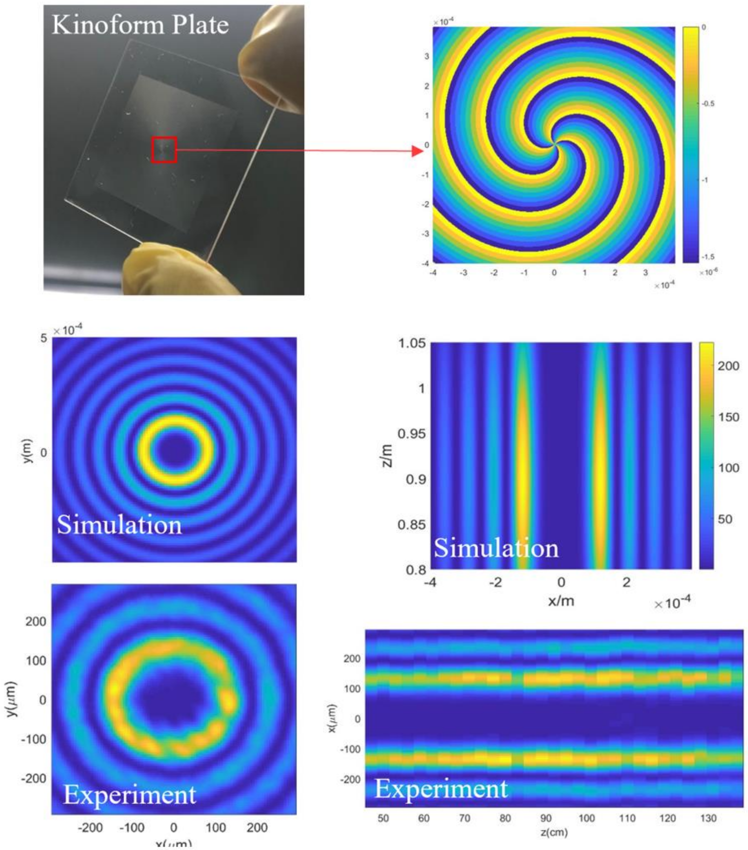
Plasma dechirper experiment @ THU



Experiment Goal:

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



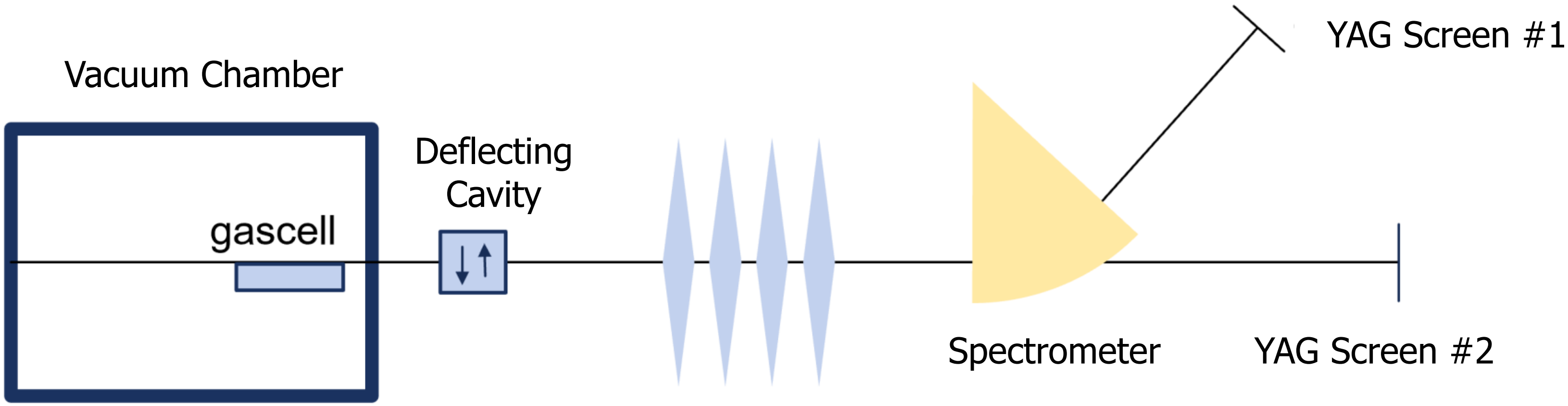


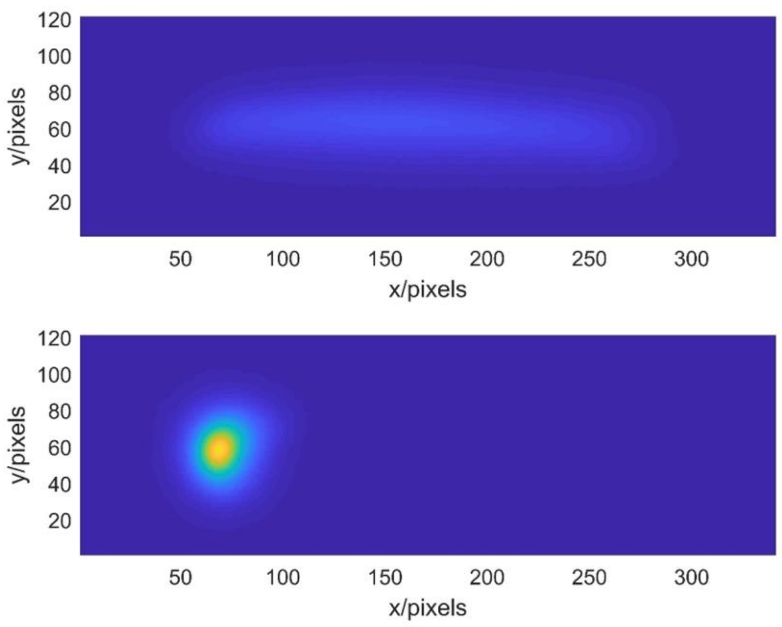
Planned to finish it before February, but delayed by COVID-19.

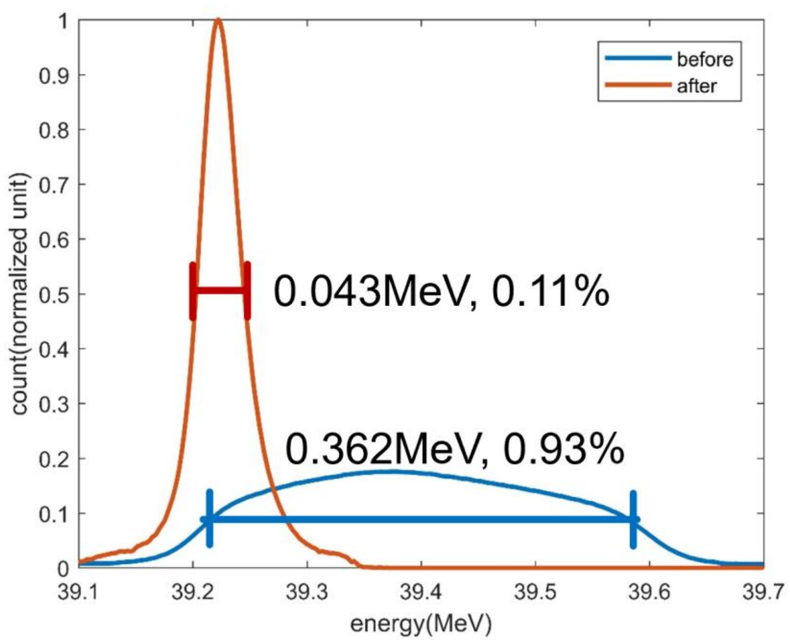
Re-started in Oct. 2020

Slides from Dr. Shuang Liu (2020)

Energy spread from 1% to 0.1%





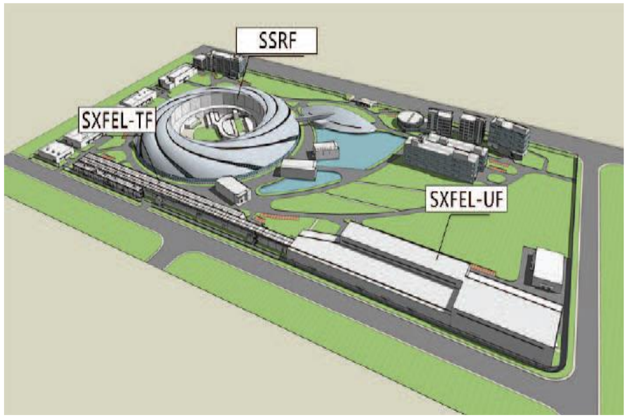


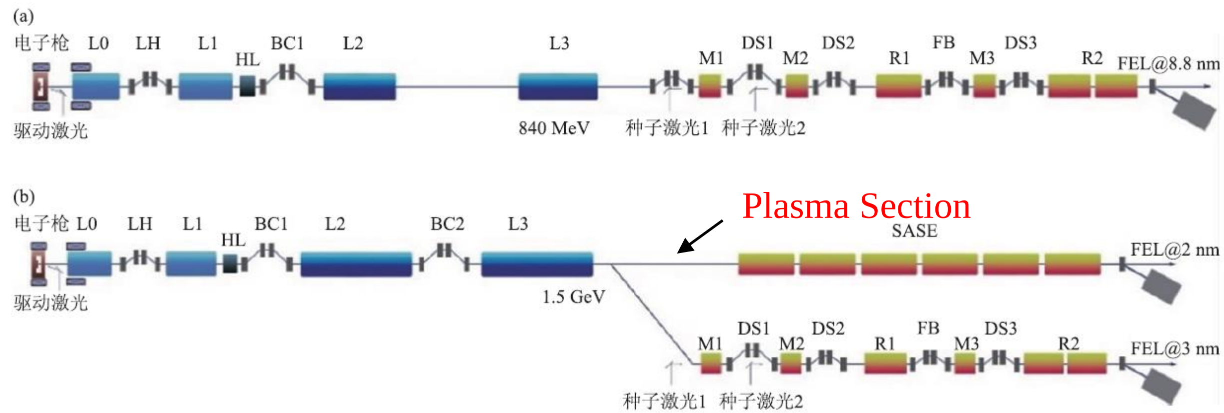
Slides from Dr. Shuang Liu (2020)

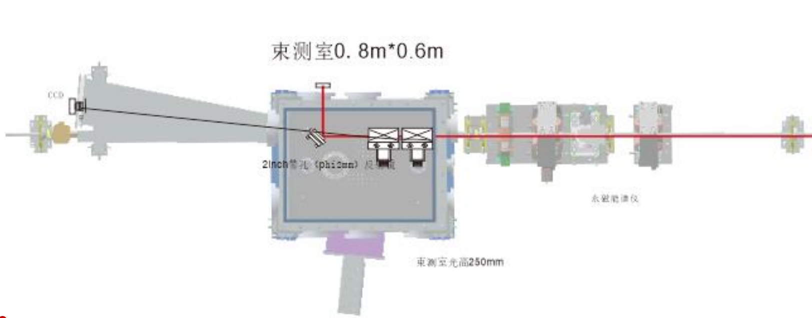
Outlines

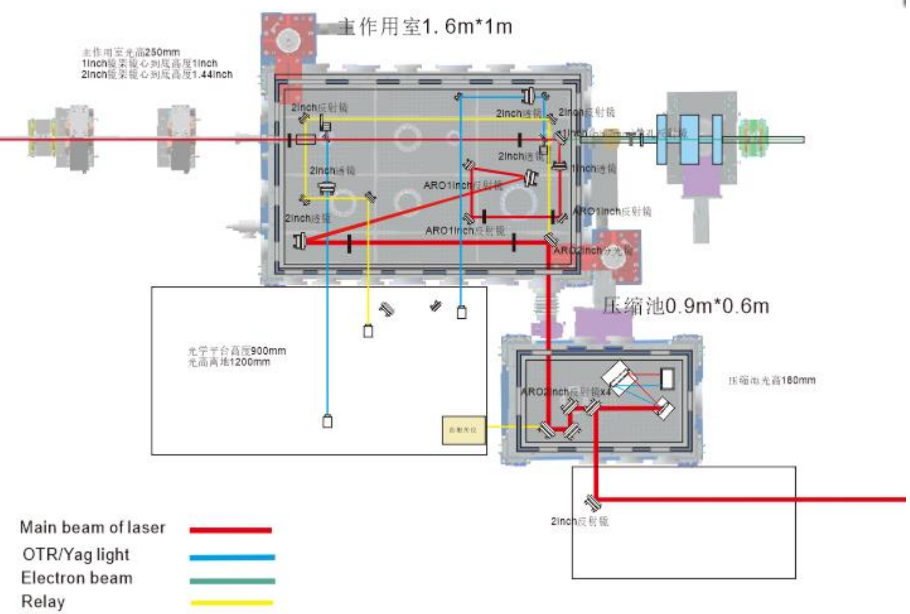
- Background: CEPC/CEPC plasma injector
- Preliminary design v2
- Current status: Simulations & experiments
- **Outlook: Future experiments**

Platform at SXFEL









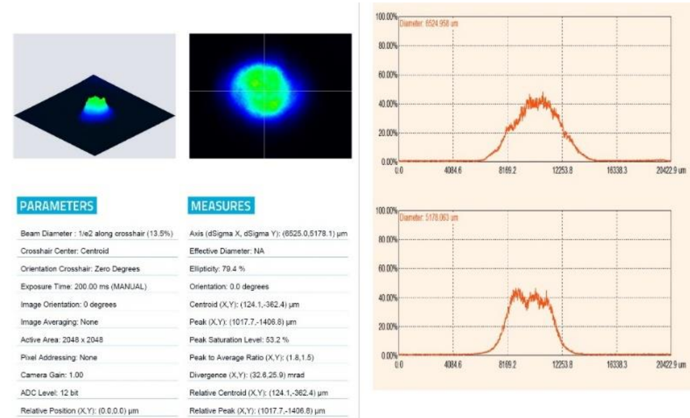
Aim:

Obtain a stable positively-chirped beam with few percent energy spread, and post-processing the beam using a passive dechirper, **to decrease the energy spread**

Laser system upgrade (finished)

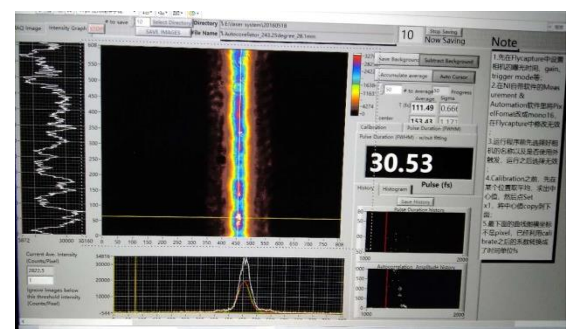
Amplifier energy performance

Amplifier output profile before expander



Pulse compressor efficiency: 72%

Pulse duration



Slides from Dr. Bo Peng (2020)

Wait for the beamtime

Slides from Dr. Bo Peng (2020)

Proposed experiments on FACET-II

SLAC National Accelerator Laboratory

FACET-II PROPOSAL

Date: Sep. 13th 2020

A. EXPERIMENT TITLE: Two Stage Cascaded High-Transformer-Ratio Plasma Wakefield Accelerator

B. PROPOSERS & REQUESTED FACILITY:

Principal Investigator:	Wei Lu, Mark Hogan, Chan Joshi, Jie Gao
Institution:	Tsinghua University, SLAC, IHEP
Contact Information:	weilu@tsinghua.edu.cn
Experiment Members:	Shiyu Zhou, Jianfei Hua, Dazhang Li
Collaborating Institutions:	
Funding Source (optional)	NSFC、DOE
Approximate Duration:	3-5years

SLAC National Accelerator Laboratory

FACET-II PROPOSAL

Date: Sep. 13th 2020

A. EXPERIMENT TITLE: Stable Mode in Hollow Channel

B. PROPOSERS & REQUESTED FACILITY:

Principal Investigator:	Wei Lu, Chan Joshi, Mark Hogan, Jie Gao
Institution:	Tsinghua/UCLA/SLAC/IHEP
Contact Information:	weilu@tsinghua.edu.cn
Experiment Members:	Shiyu Zhou, Jianfei Hua, Dazhang Li,
Collaborating Institutions:	
Funding Source (optional)	NSFC、DOE
Approximate Duration:	3 years

E-mail from Prof. Mark Hogan, head of plasma acc. group in SLAC

Hello Wei,

So good to hear from you! I very much agree that these are important ideas that can be very impactful for our field. I want to do everything we can to ensure that the proposals are highly reviewed and that we develop a plan that ensures the best chance of success.

Two proposals has been reviewed last year, and both got "good" remarks

Summary and prospects

- **HTR e- acceleration**
  - Start-to-end simulation performed, CPI requirement to linac updated
  - Preliminary results for single-parameter error analysis
  - Detailed analysis is ongoing, multi-parameter effects under consideration
  - Linac can not meet the CPI requirement yet, both sides work on it
  - For plasma accelerator, lower plasma density or lower TR can help
- **e+ acceleration**
  - More schemes are under consideration
  - Detailed error analysis and linac design should be finished in 2021
- **Experiments affected by COVID-19, but almost recovered now**
  - Test facility for PWFA is crucial and under consideration
- **Feasibility report (2022-2023) → TDR: Still a long way to go**

Thank you!