中國科學院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Recent Progress on CEPC Plasma Injector

Prof. Wei Lu @ THU and Dazhang Li @ IHEP, CAS

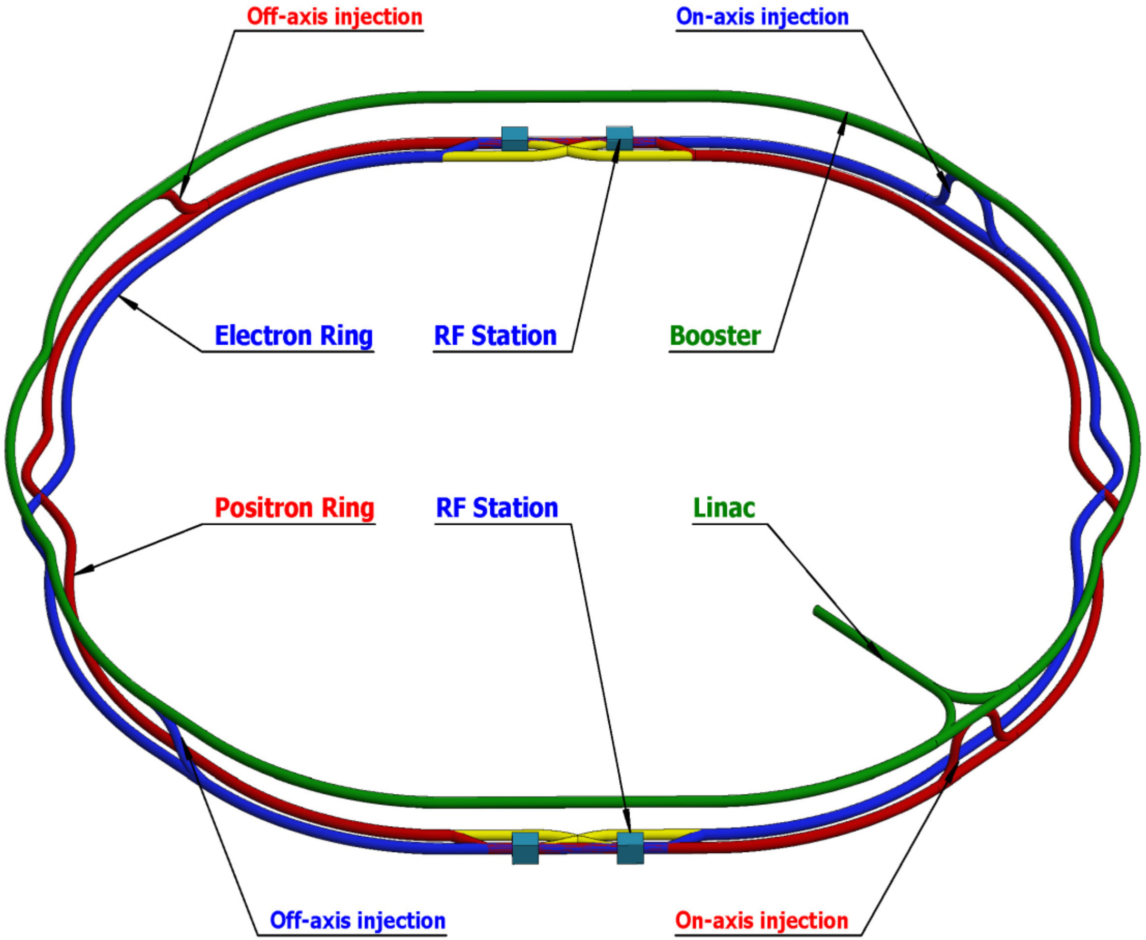
On behalf of the IHEP-THU-BNU AARG team

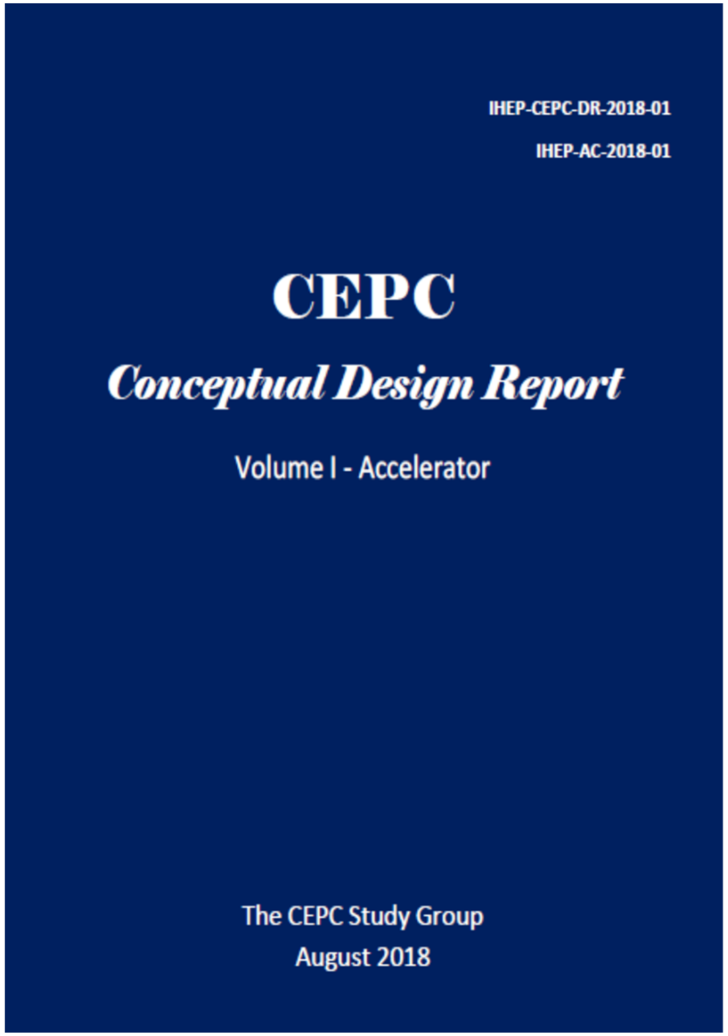
Nov. 11, 2021

Outlines

- Background: CEPC/CEPC plasma injector
- Current status: Simulations & experiments
- Outlook: Future schedule towards TDR

Circular Electron Positron Collider





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

Low field Dipole Problem in Booster

Right now, the CEPC linac baseline has been changed. The linac will provide 20 GeV beams instead of 10 GeV.

Can we use a 10m scale plasma accelerator to boost the beams' energy from 10GeV to 20 GeV or higher?

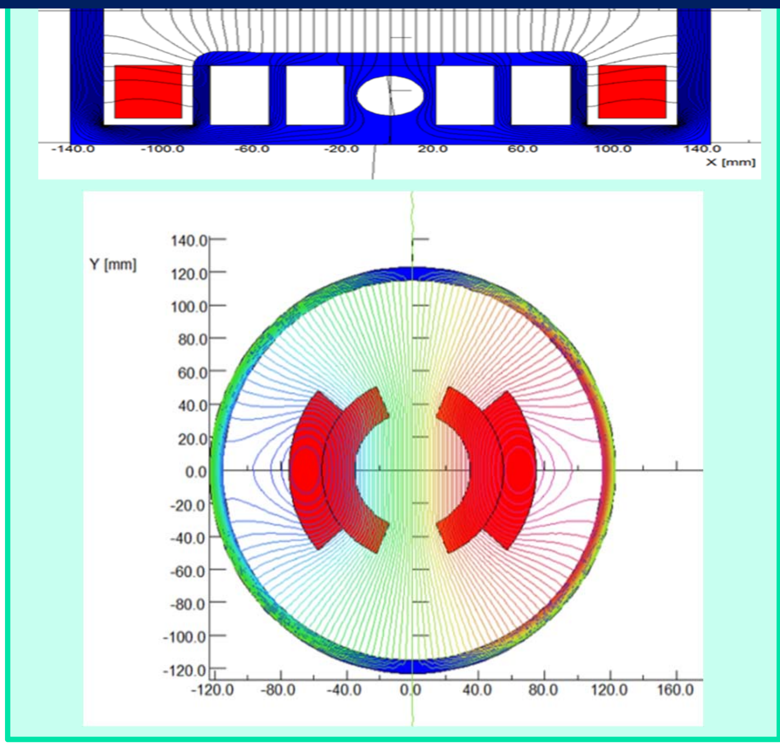
measure

- The Earth field ~0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

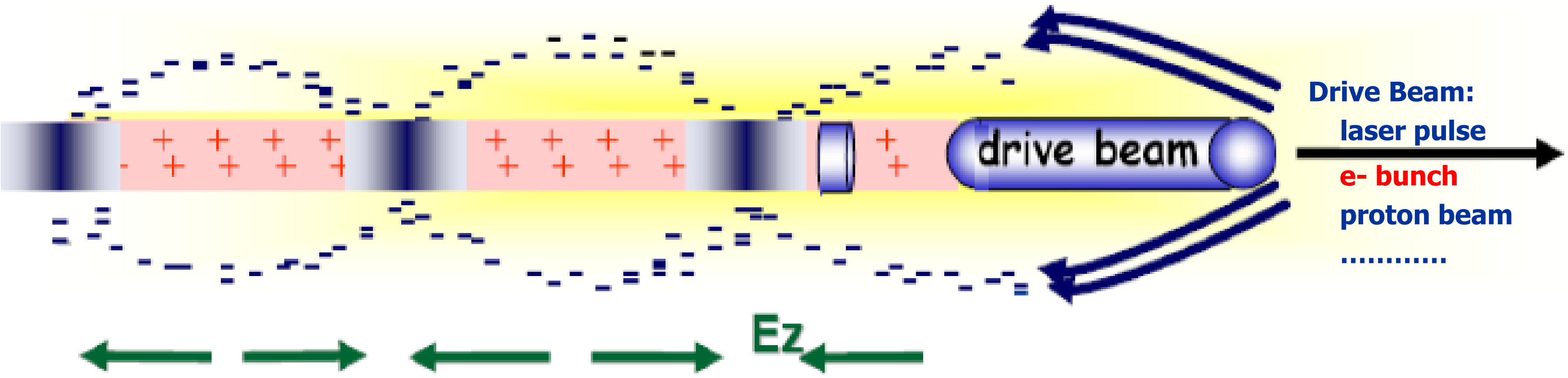
➢ Thinking beyond CDR

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

  - Sextupole coils outside vacuum chamber



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: $\Delta P_{ave} \sim 3\text{kW}$

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

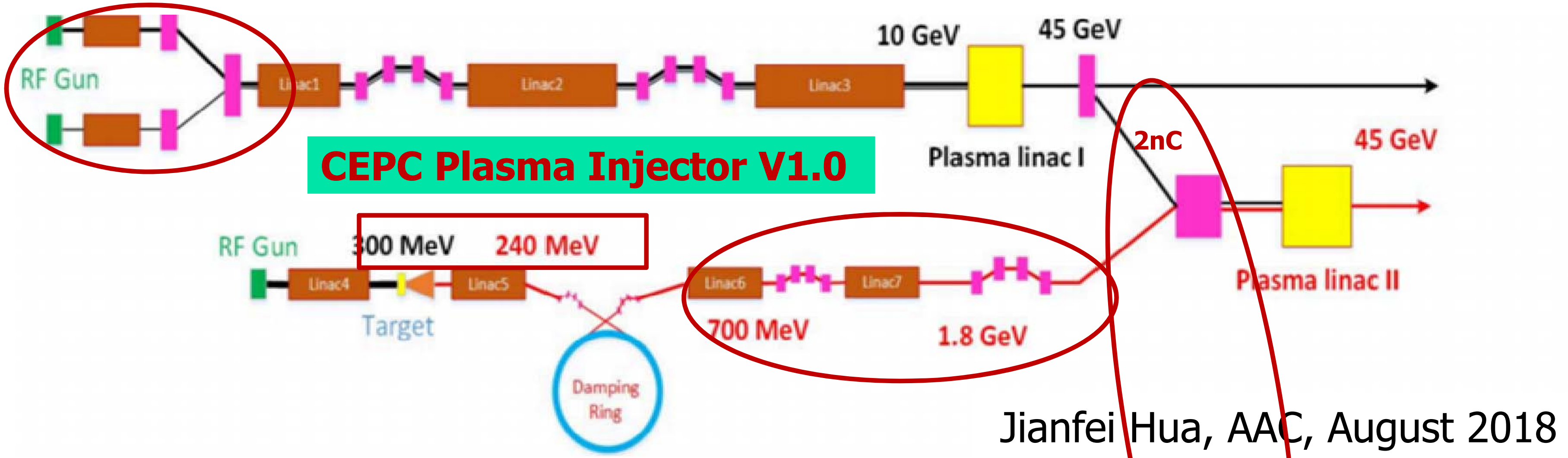
Since 2017

- **THU team:**
  - Prof.: W. Lu, J. F. Hua,
  - Staff: Dr. S. Y. Zhou, S. Liu, Y. Ma, Y. P. Wu
  - PhD: B. Peng, T. L. Zhang, H. Y. Xiao, Z. Song, Y. Fang, F. Yang......

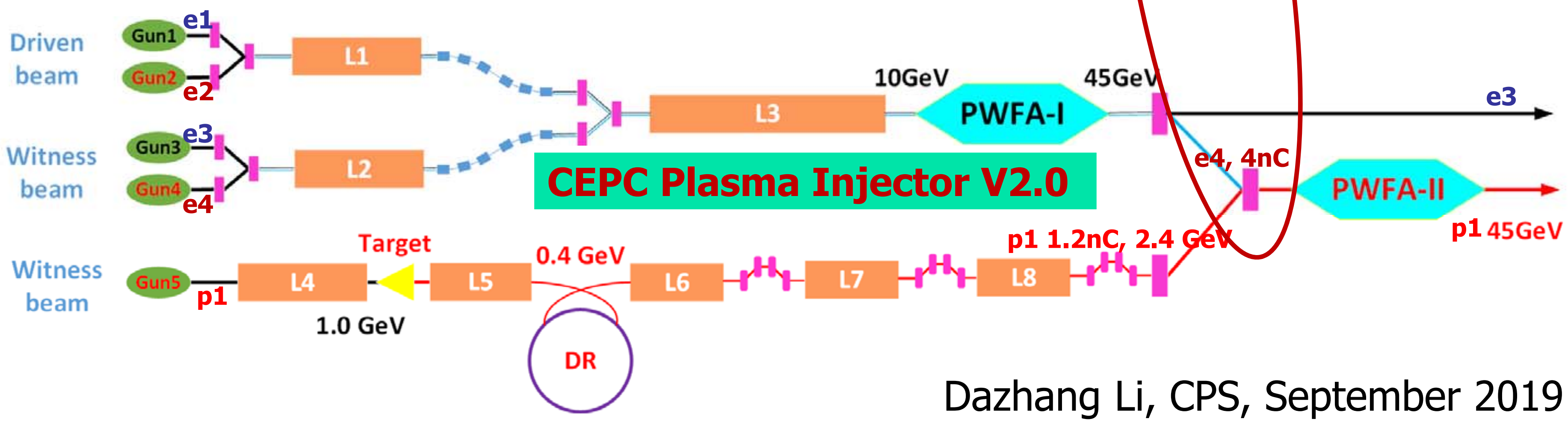
- **IHEP team:**
  - Prof.: J. Gao, Y. H. Li, J. R. Zhang, Y. S. Huang, X. P. Li
  - Staff: D. Z. Li, M. Zeng, D. Wang, C. Meng, Y. W. Wang, X. H. Cui, G. Shu
  - PhD: X. N. Wang, J. Wang, Y. L. Liu

- **BNU team:**
  - Prof. W. M. An and Dr. J. G. Huang

CPI conceptual Design V1.0→V2.0



Jianfei Hua, AAC, August 2018

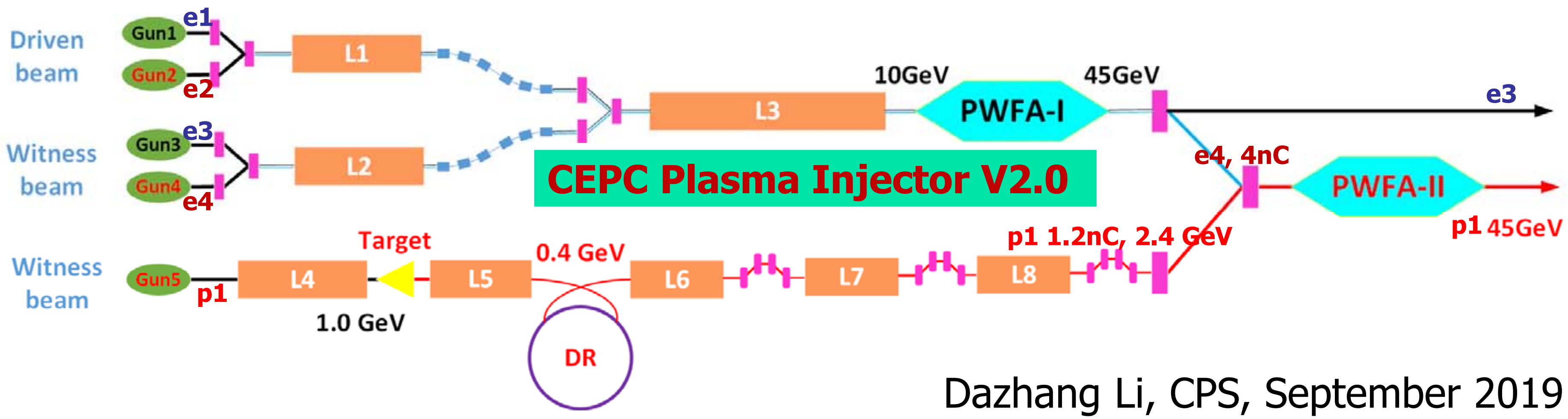


Dazhang Li, CPS, September 2019

Requirement & Key issues of CPI

Booster Requirement	
Energy (GeV)	45.5 (0.2%)
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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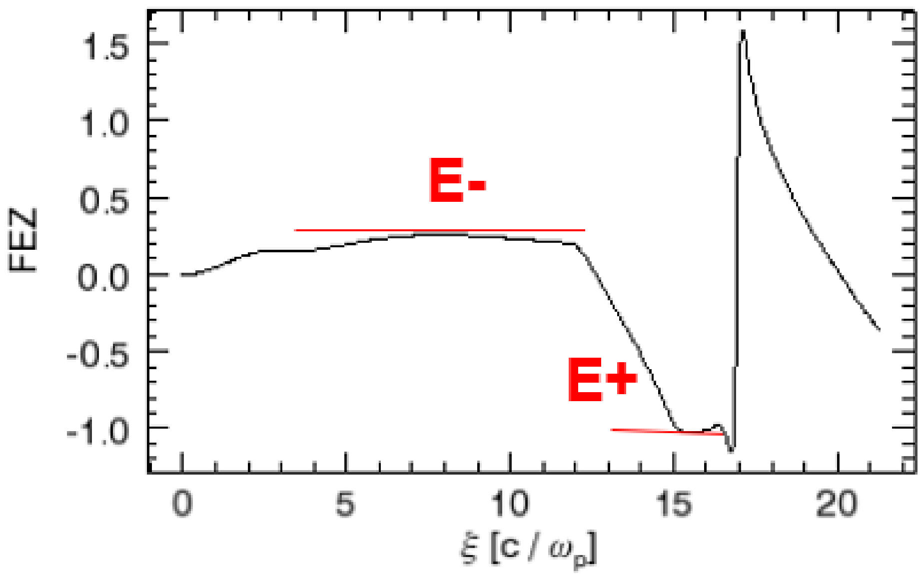
What is High Transformer Ratio?



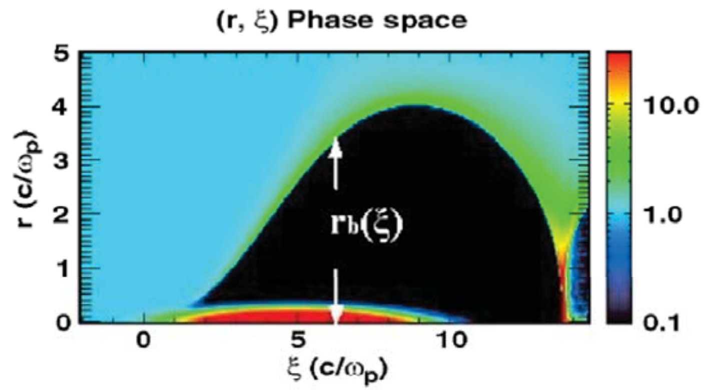
$$TR = E^{+}/E^{-}$$

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

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

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

HIGH TRANSFORMER RATIO



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

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

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

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

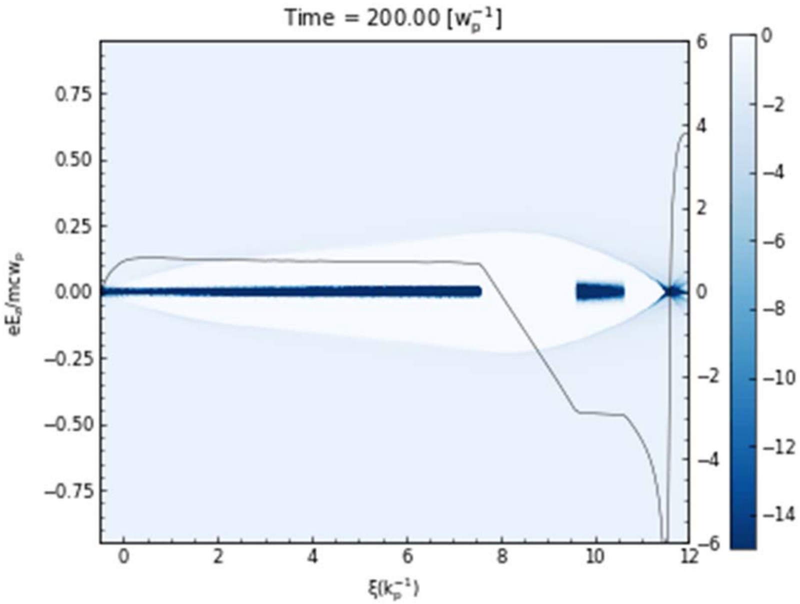
HTR mode, TR ≥ (45-10)/10=3.5

LTR mode, TR ≥ (20-10)/10=1

HTR e- Acceleration— ideal case

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**
- **Assuming fully symmetric drive beam!**

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

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

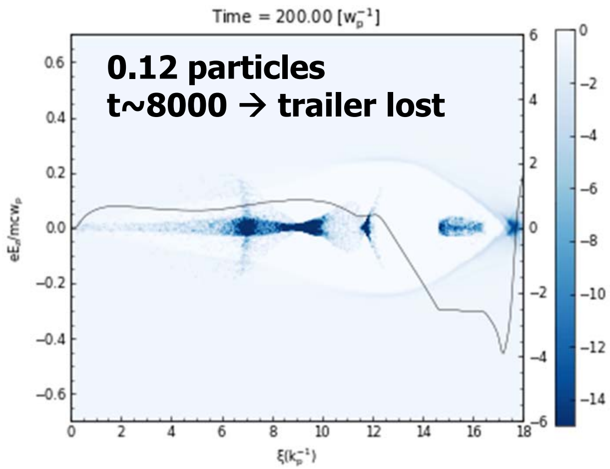
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

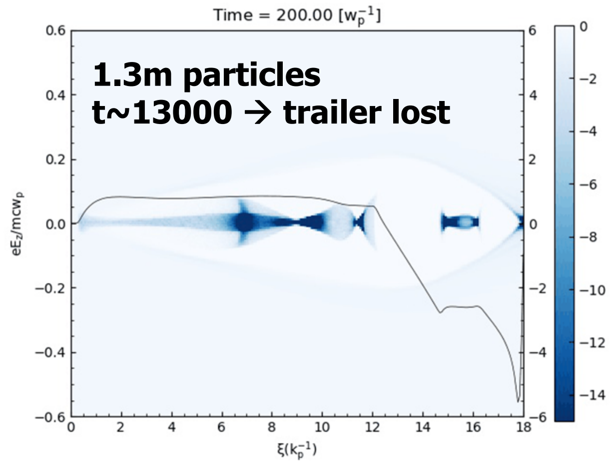
Initial noise simulation vs. real case

- An important question is "How do the beams evolve from their initial statistical noise?"
- Another question is "Does the hosing instability set any limit on the transformer ratio of PWFA?"

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 $N(0,\ \sigma_r/\sqrt{N})$
- For PIC simulation, number of macro particle is much less than practical particle number, so the initial noise level is different in magnitudes.
- For a 5.8nC driver, the particle number in QuickPIC is $128 \times 128 \times 256$, which is $1/93^2$ of the practical particle number.





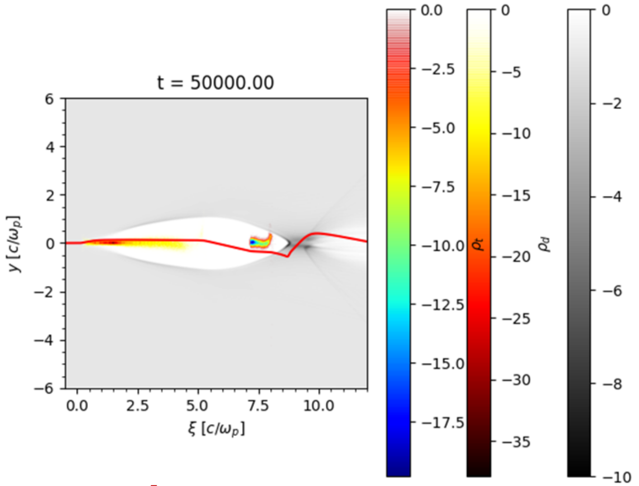
If not fully symmetry……

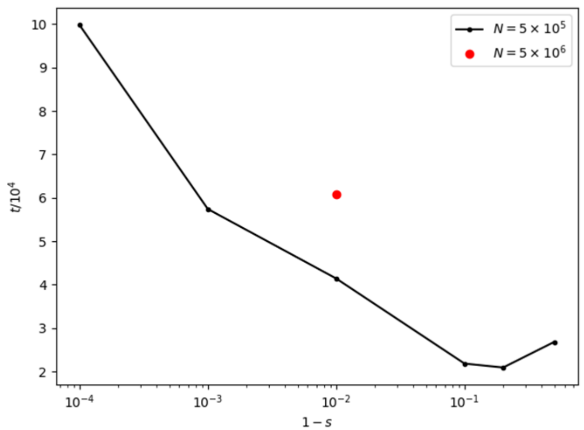
In the QuickPIC simulation, if the drive beam is not fully symmetry, even let $\langle x_d \rangle = 0$, the hosing instability occurs much earlier than ideal case. For example, adding only 0.025nm slice jitter to drive beam leads to severe hosing instability. Is it physical or not?

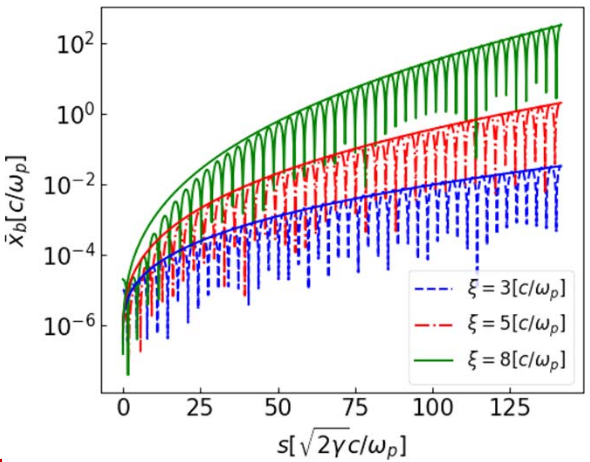
We did different studies and found that:

- Increase particle number → hosing improved
- Increase the jitter (noise) to dx level or larger → hosing became more serious
- Fully asymmetry to partial asymmetry → hosing improved

It seems physical. How can we evaluate / avoid / damping / the hosing instability?



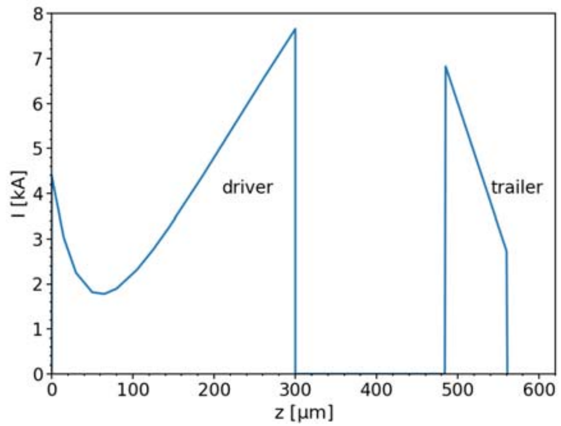


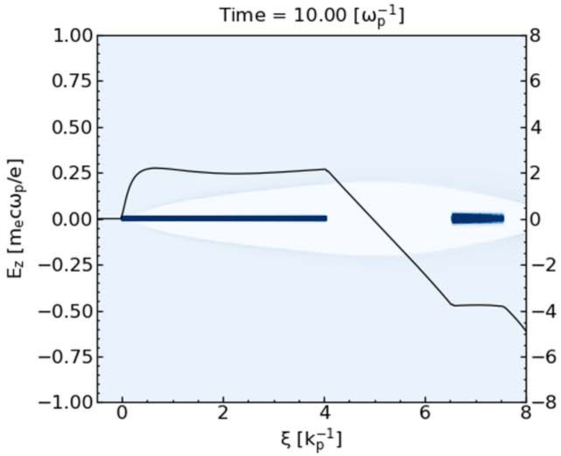


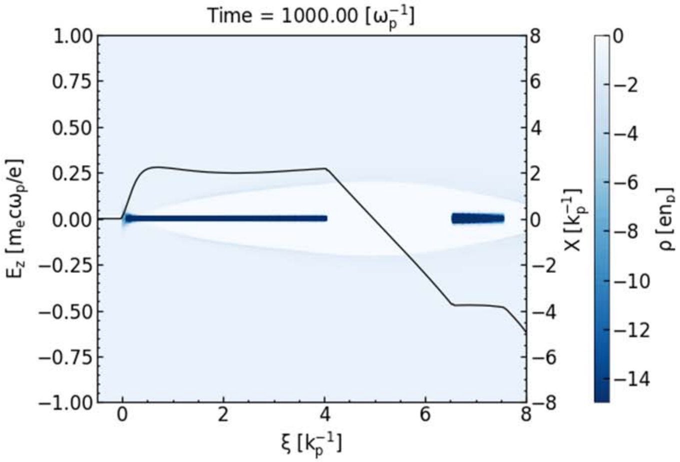
5×10^5 particles 99.99% symmetry $\sigma_z \sim 5$ lose 50% particles at 100000 ω_p^{-1}

Slide from Dr. X. N. Wang and Prof. W. M. An (2020); Dr. M. Zeng (2021)

Short driver for more stable acc.







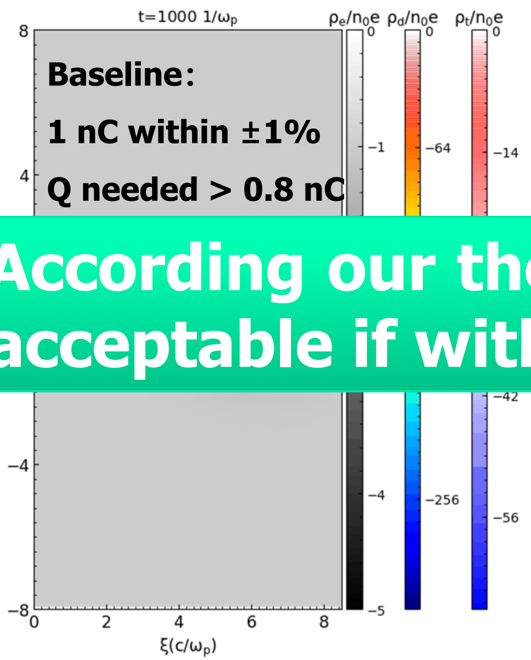
beam	Driver	Trailer
plasma density $n_p(\times 10^{16} cm^{-3})$	0.50334	
Driver energy $E(GeV)$	10	10
Normalized emittance $\epsilon_n(mm\ mrad)$	20	100
Length(um)	300	77
(matched)Spot size(um)	3.87	8.65
Charge(nC)	5.8→4	0.84→1.24
Energy spread $\delta_E(\%)$	0	0
Beam distance(um)	149→184	

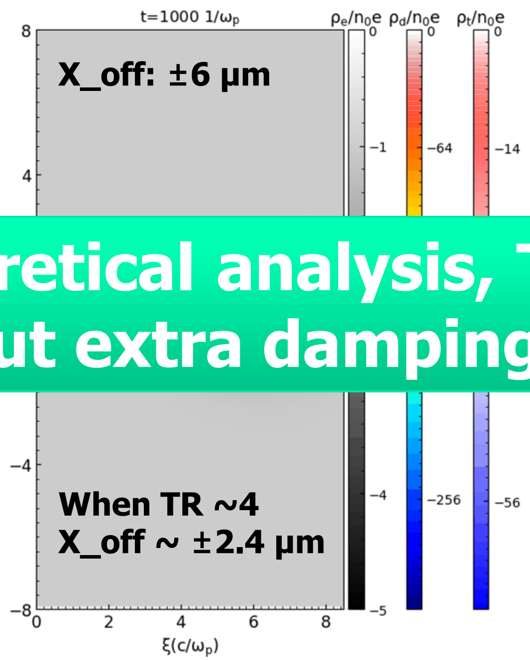
	V1.0 HTR	V2.0 LTR
Accelerating distance (m)	10.7	4.8
Trailer energy $E(GeV)$	45.5	25
Normalized emittance $\epsilon_n(mm\ mrad)$	98.36	100
Charge(nC)	0.84	1.21
Energy spread $\delta_E(\%)$	0.40	1
TR	~ 4	~ 1.6
Efficiency(%) (driver -> trailer)	60.0	54.0

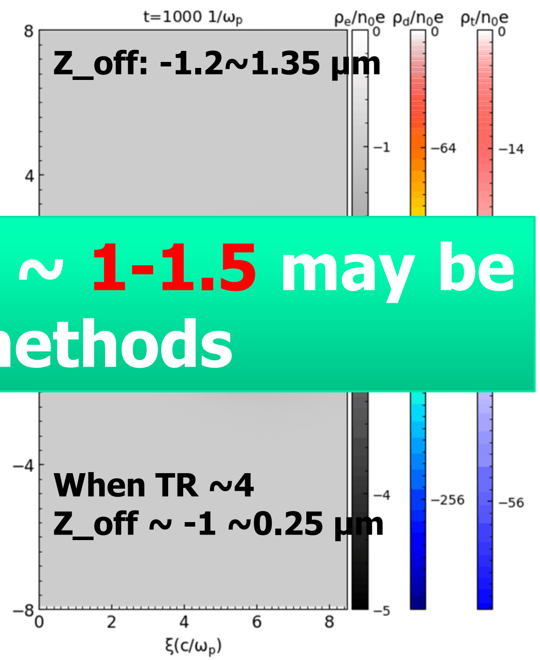
Slide from Dr. X. N. Wang, Dr. S. Y. Zhou and Prof. W. M. An (2021)

Backup scheme with TR ~ 1.5

Asymmetry Ratio	Energy	Emittance (mm·mrad)	Bunch charge (0.2%)	Bunch charge (2%)	rms Energy spread
0	25.02 GeV	100 / 100	0.45 nC	1.36 nC	0.4%
0.1%	24.97 GeV	111 / 108	0.36 nC	1.36 nC	0.4%
1%	24.93 GeV	174 / 163	0.28 nC	1.36 nC	0.44%
2.5%	24.89 GeV	431 / 294	0.24 nC	1.33 nC	0.62%
10%	25.45 GeV	1057 / 1659	0.03 nC	0.28 nC	2.79%
2.5% (baseline)	26.25 GeV	645 / 496	1 nC (26.25 ±1%), TR ~ 1.76, η~52%		0.86%



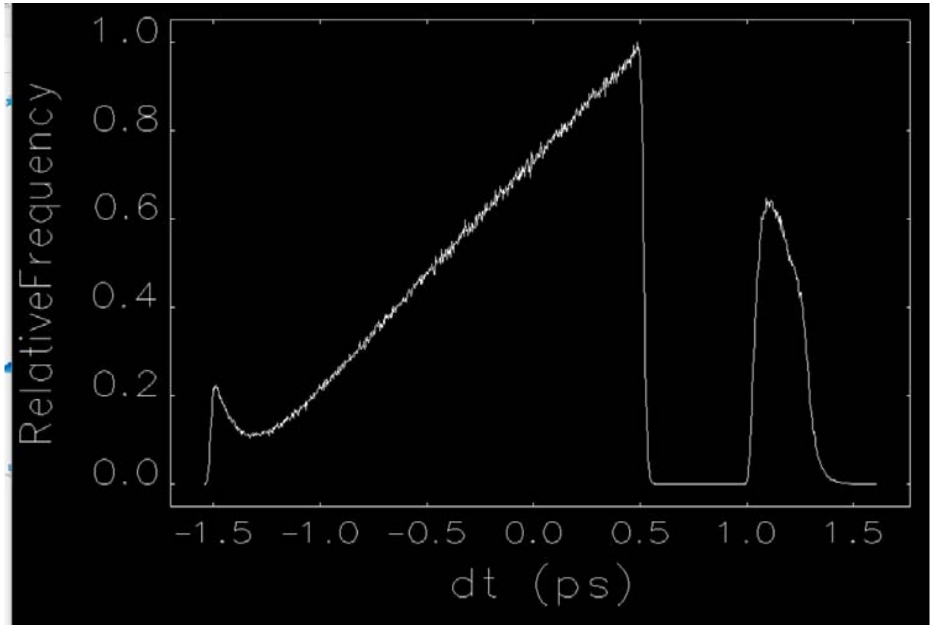


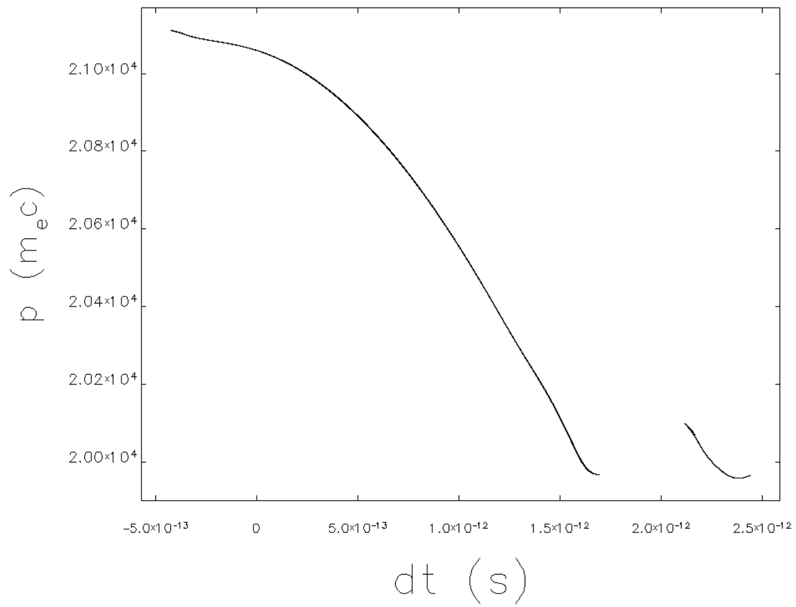


According our theoretical analysis, TR ~ 1-1.5 may be acceptable if without extra damping methods

Linac optimization for ideal beams

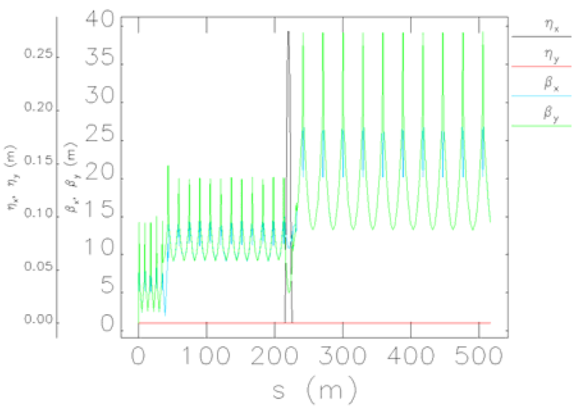
- Main Linac (Scheme-I)
  - ✓ If RF gun can provide electron beam with required shape, the main linac just accelerate beam to 10GeV.
  - ✓ Acceleration:
    - The longitudinal shape could be almost maintained
    - Short-range longitudinal wakefield + short bunch length + high bunch charge
      - Energy spread: 1.8% → Difficult design for FFS

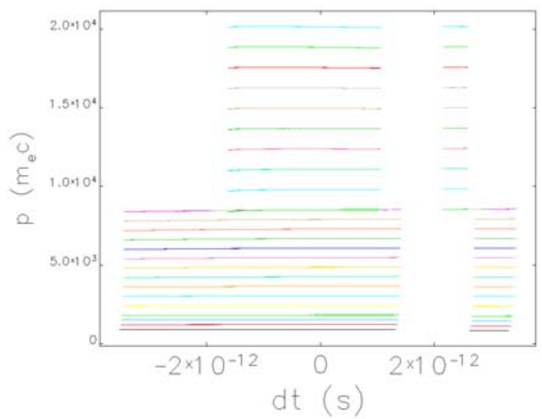


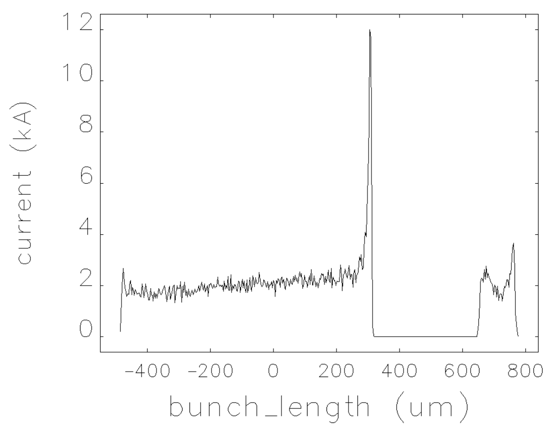


Linac optimization for ideal beams

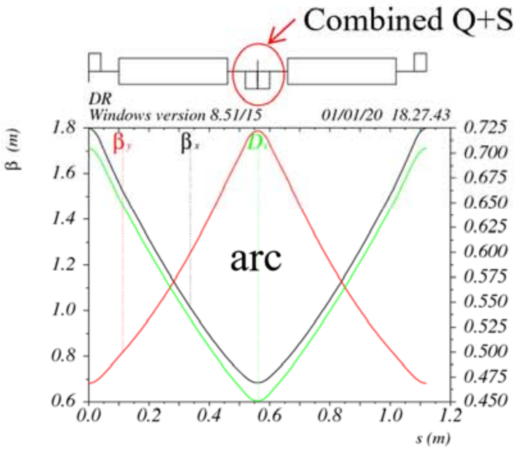
- Main Linac (Scheme-II)
  - ✓ In order to decrease the energy spread and more flexible and compatible with other beam shaping scheme, one bunch compressor is introduced
    - Long bunch length beam + bunch compressor +short bunch length beam acceleration
    - High accelerating gradient s-band accelerating structure: 27MV/m
    - Energy spread: 0.275%
  - ✓ Longitudinal deformation, need more optimization

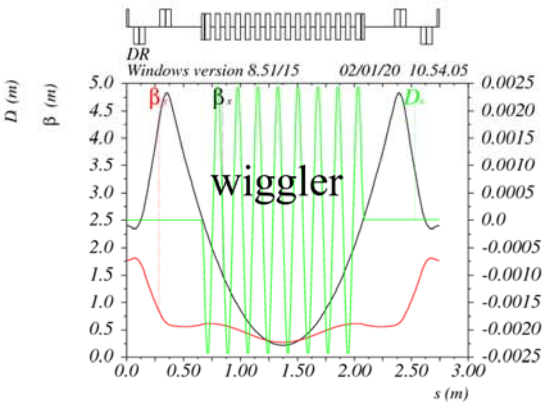


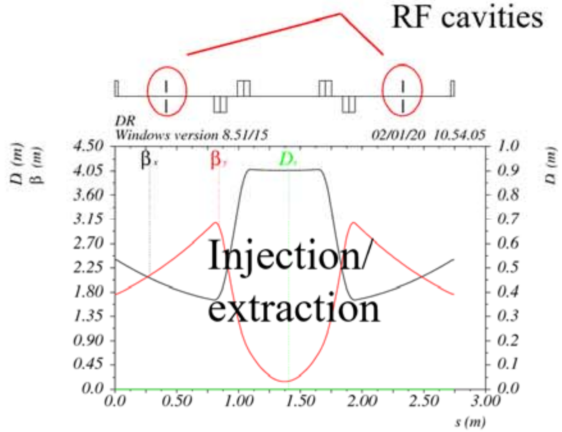


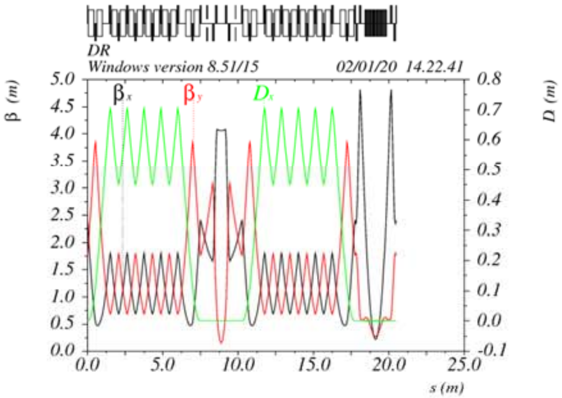


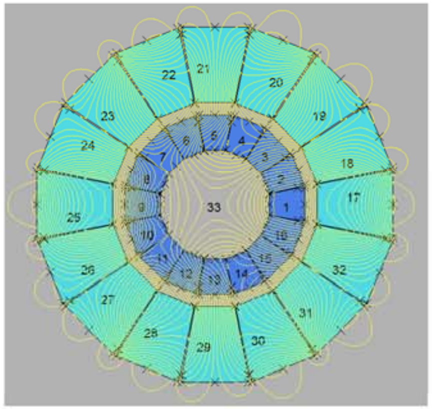
Damping Ring Optics Design V3.0



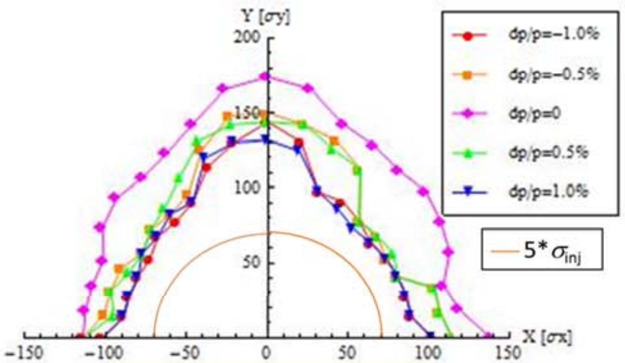








Dynamic Aperture



$\nu_x / \nu_y = 3.16/3.21$

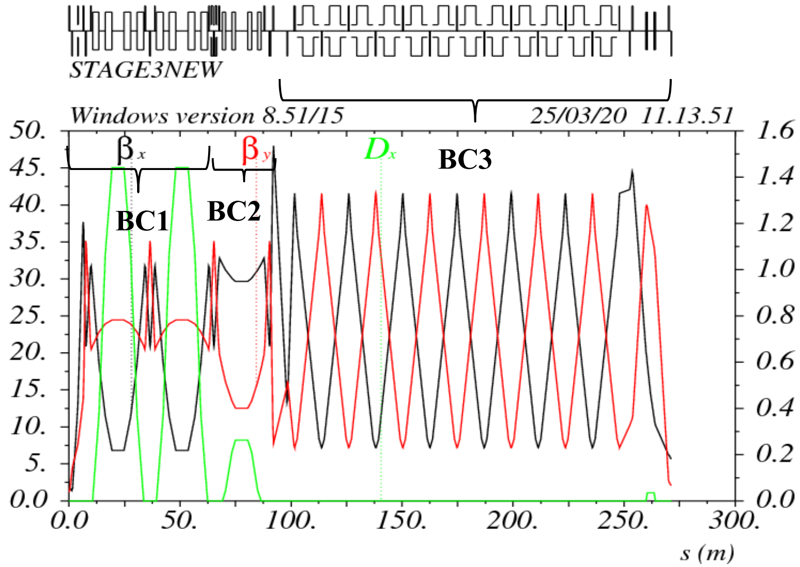
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

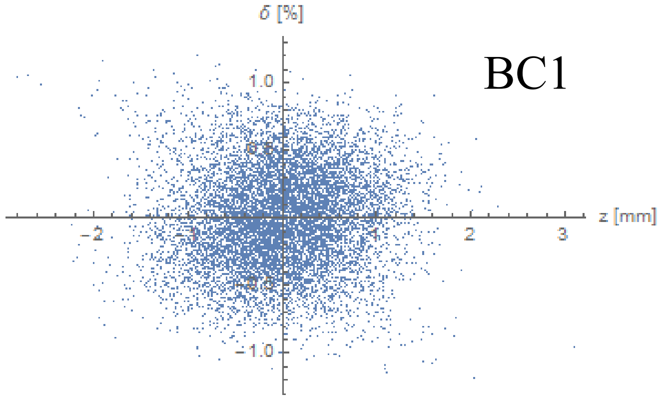
By Dr. Dou Wang and Cai Meng from IHEP (2020)

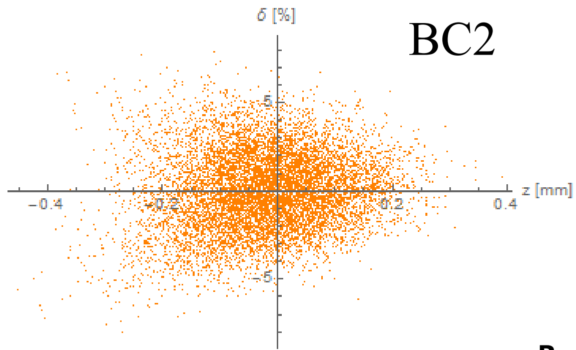
3-Stage Bunch Compressor

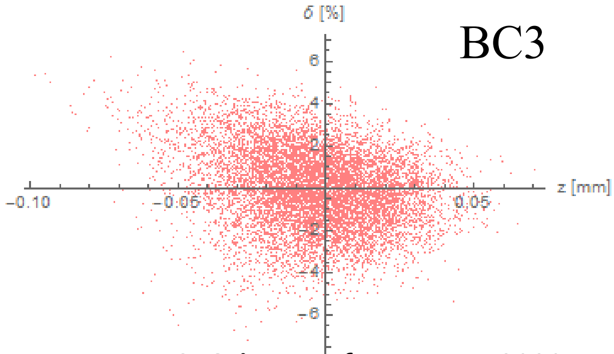
	BCI	BCII	BCIII
Initial energy (MeV)	400	400.1	405
δinj (%)	0.05	0.367	2.17
Initial σz (mm)	4.4	600	100
f_{RF} (GHz)	2.860	5.712	5.712
Voltage(GV)	0.0056	0.12	4.18
Gradient (MV/m)	20	40	40
L (m)	0.28	3	104
ϕ_{RF} (degree)	89	88	61.5
R_{56} (mm)	1200	27.6	5.5
Final energy(MeV)	400.1	405	2400
δext (%)	0.367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







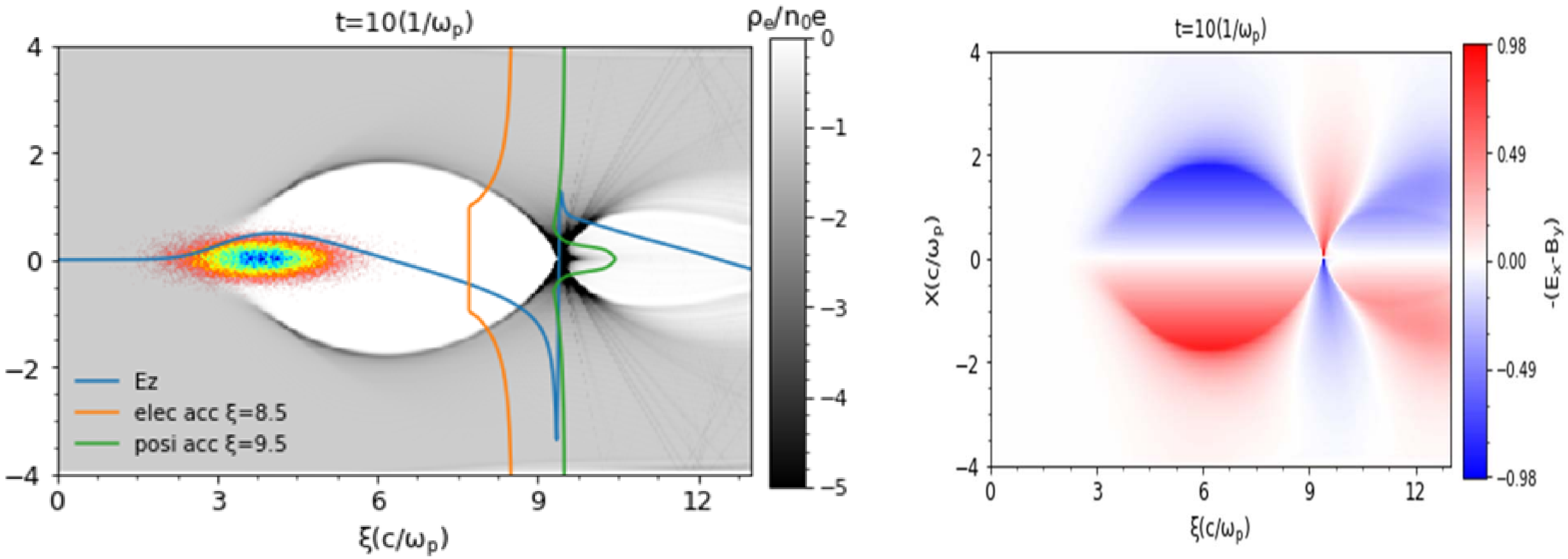


By Dr. Dou Wang & Cai Meng from IHEP (2020)

Basic ideas for improving e+ acc.

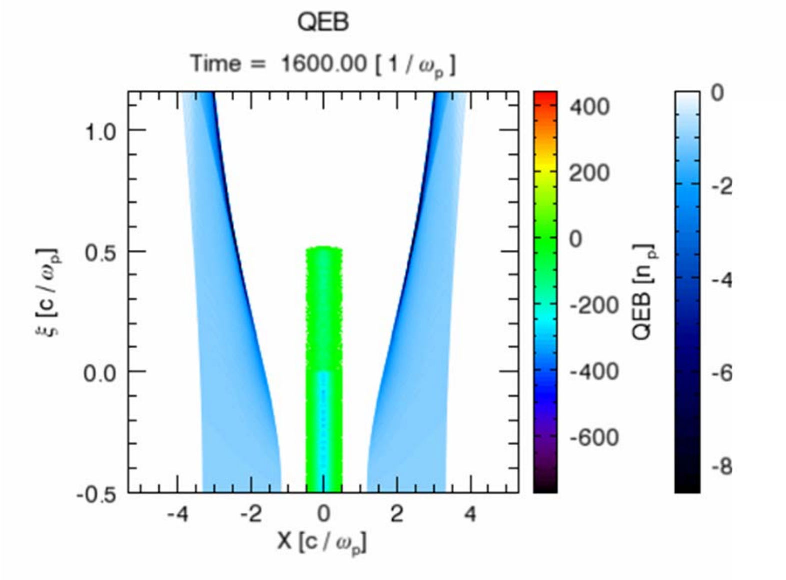
A "perfect" wakefield means:

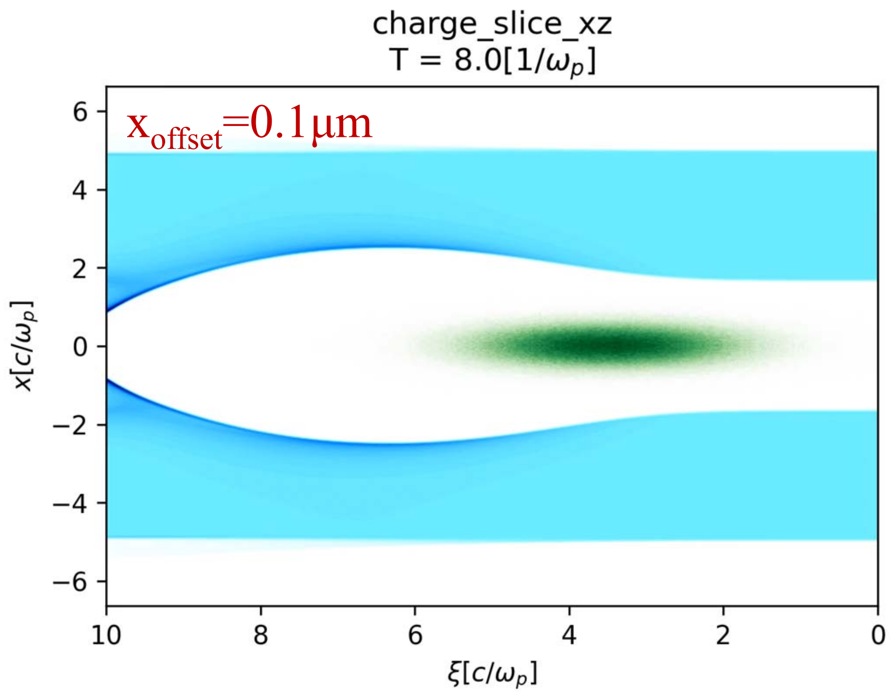
- **Flat longitudinal wakefield, particles at different position experience same Ez**
- **Transverse wakefield can provide focusing forces to the accelerated particles**



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

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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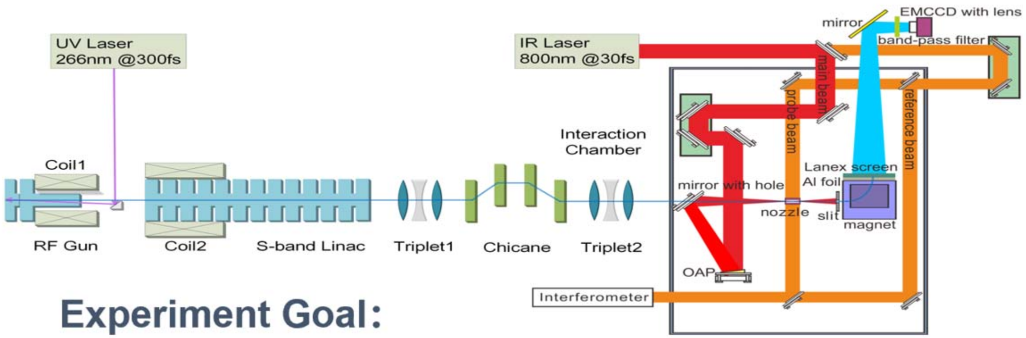
Plasma wakefield acceleration in the blowout regime is particularly promising for high-energy acceleration of electron beams because of its potential to simultaneously provide large acceleration gradients and high energy transfer efficiency while maintaining excellent beam quality. However, no equivalent 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.

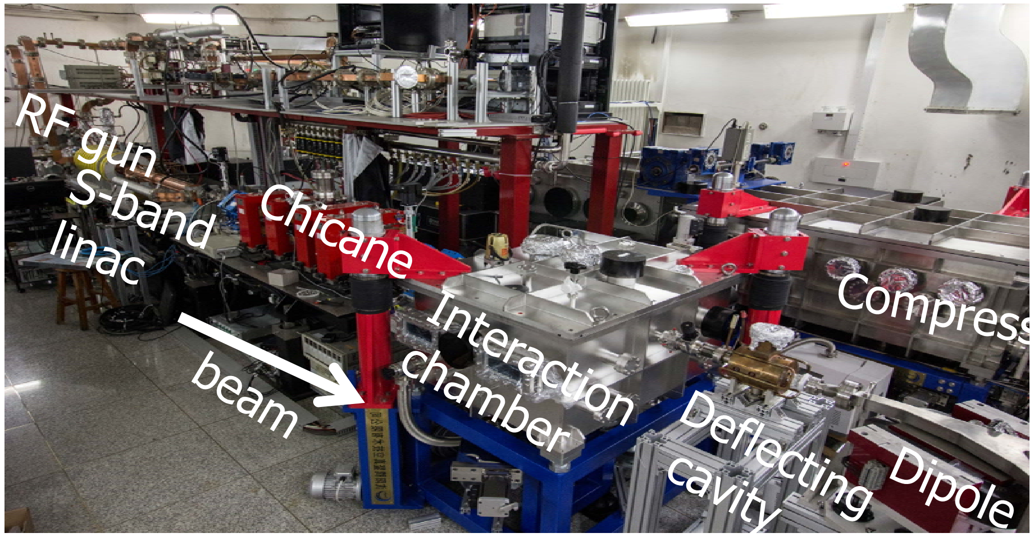
DOI: 10.1103/PhysRevLett.127.174801

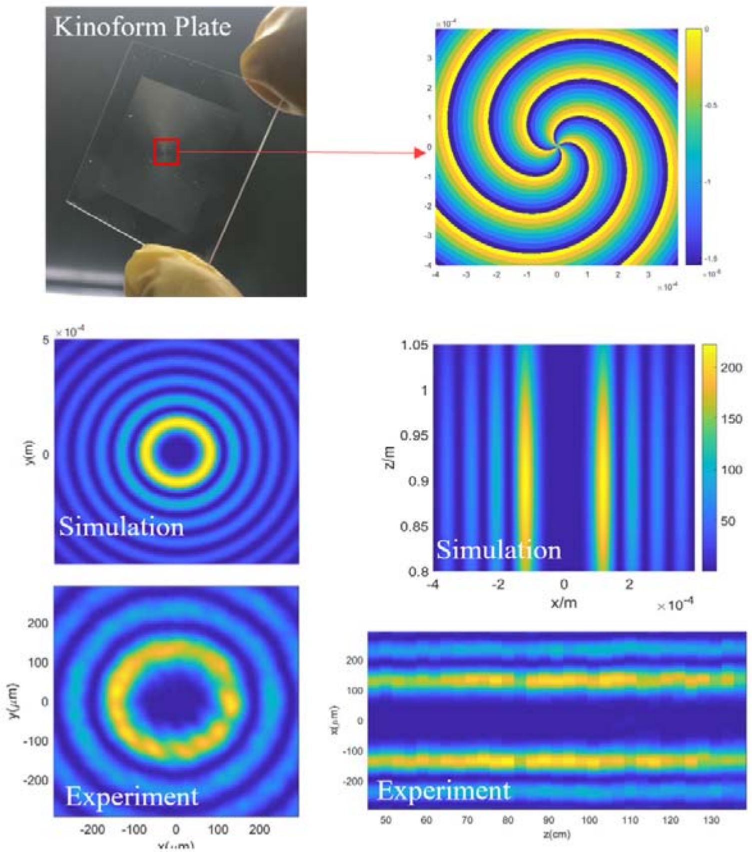
Plasma dechirper experiment @ THU



Experiment Goal:

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



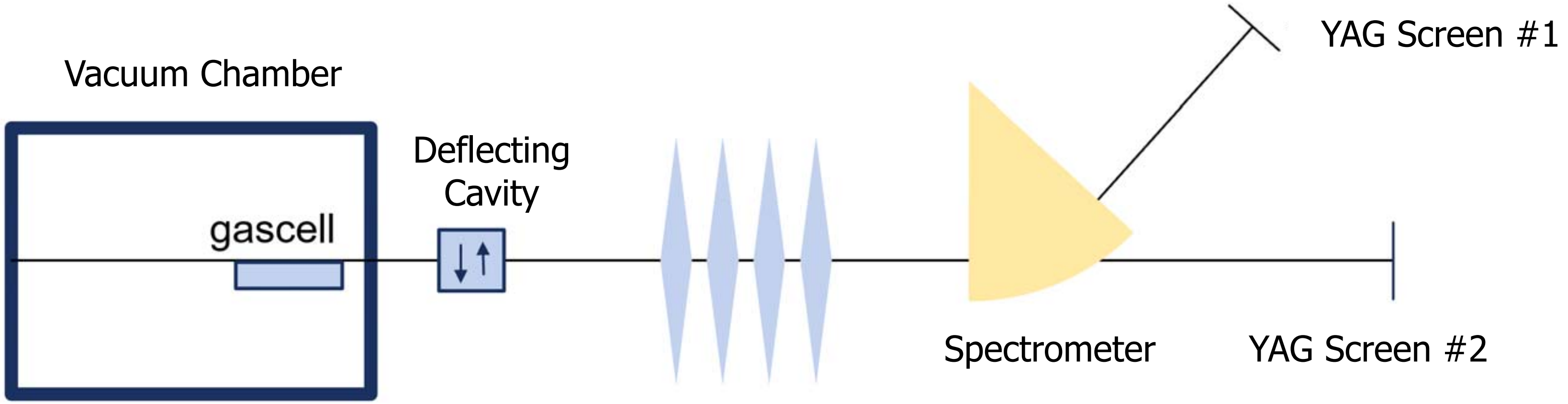


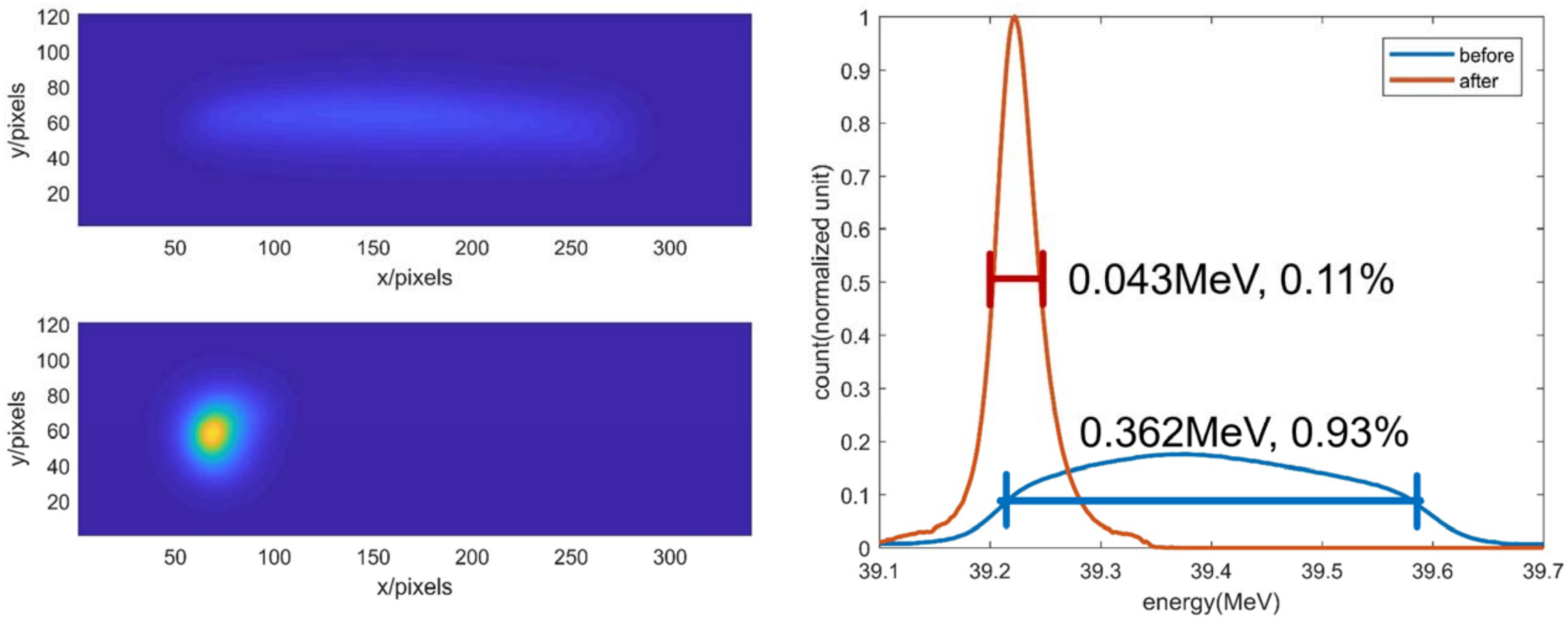
Planned to finish it before February, but delayed by COVID-19.

Re-started in Oct. 2020

Slides from Dr. Shuang Liu (2020)

Energy spread from 1% to 0.1%



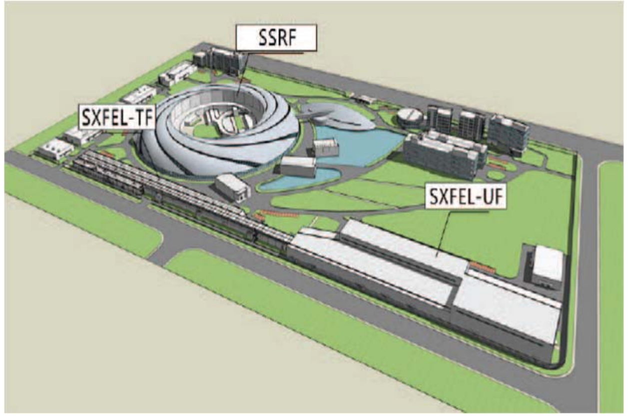


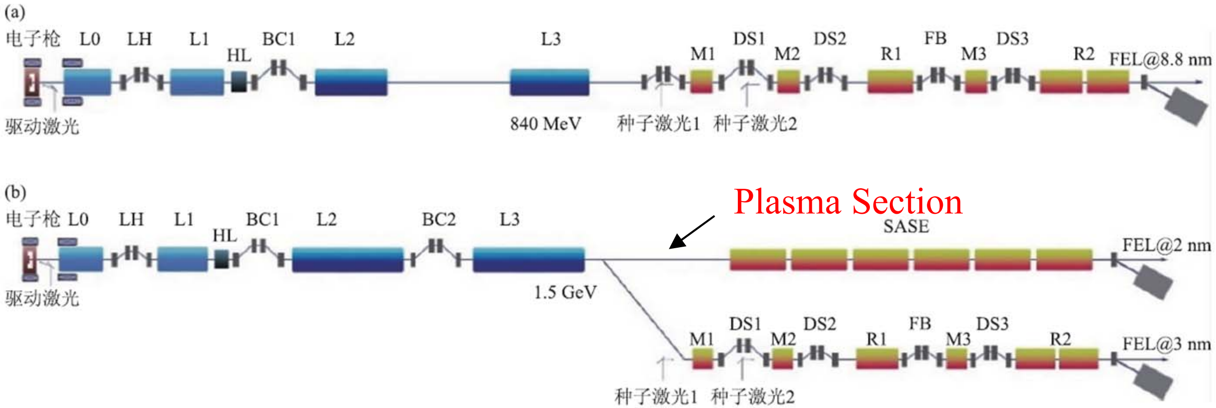
Slides from Dr. Shuang Liu (2020)

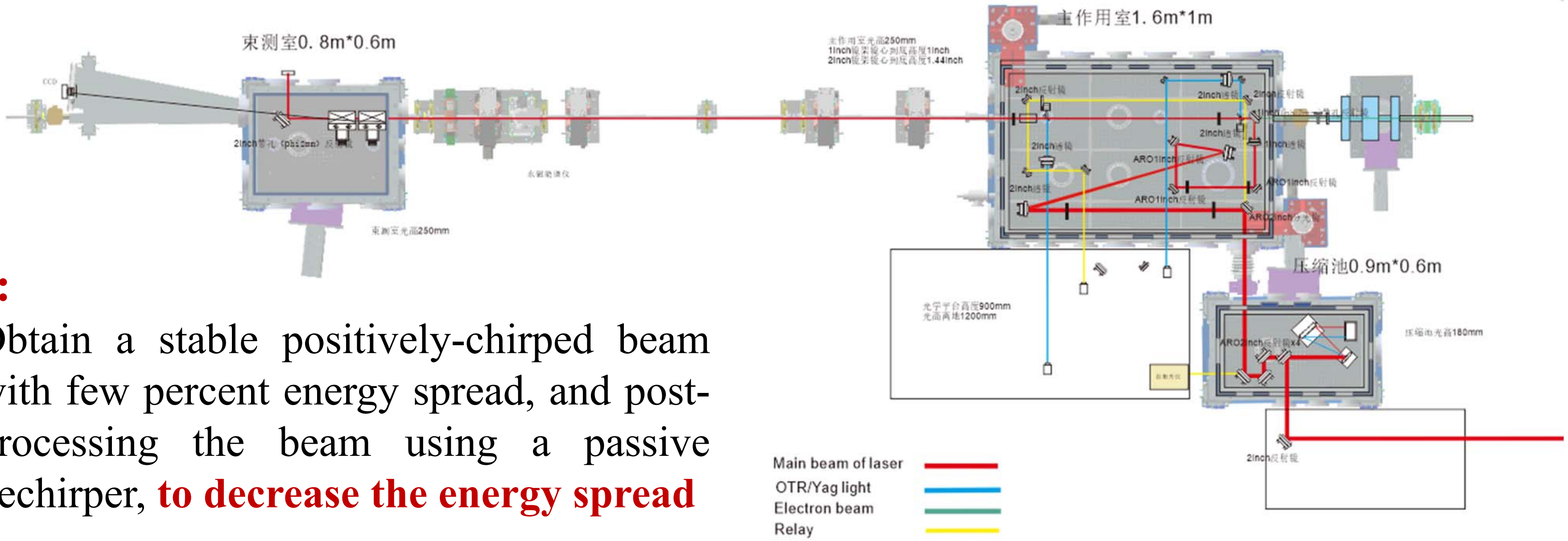
Outlines

- Background: CEPC/CEPC plasma injector
- Current status: Simulations & experiments
- **Outlook: Future schedule towards TDR**

Platform at SXFEL







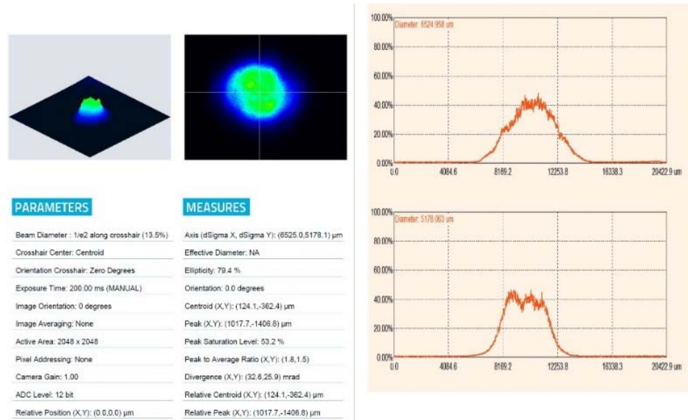
Aim:

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)

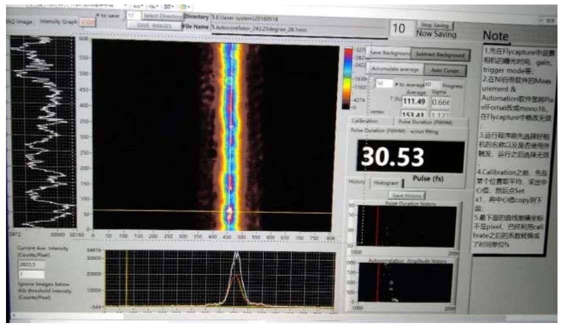
Amplifier energy performance

Amplifier output profile before expander



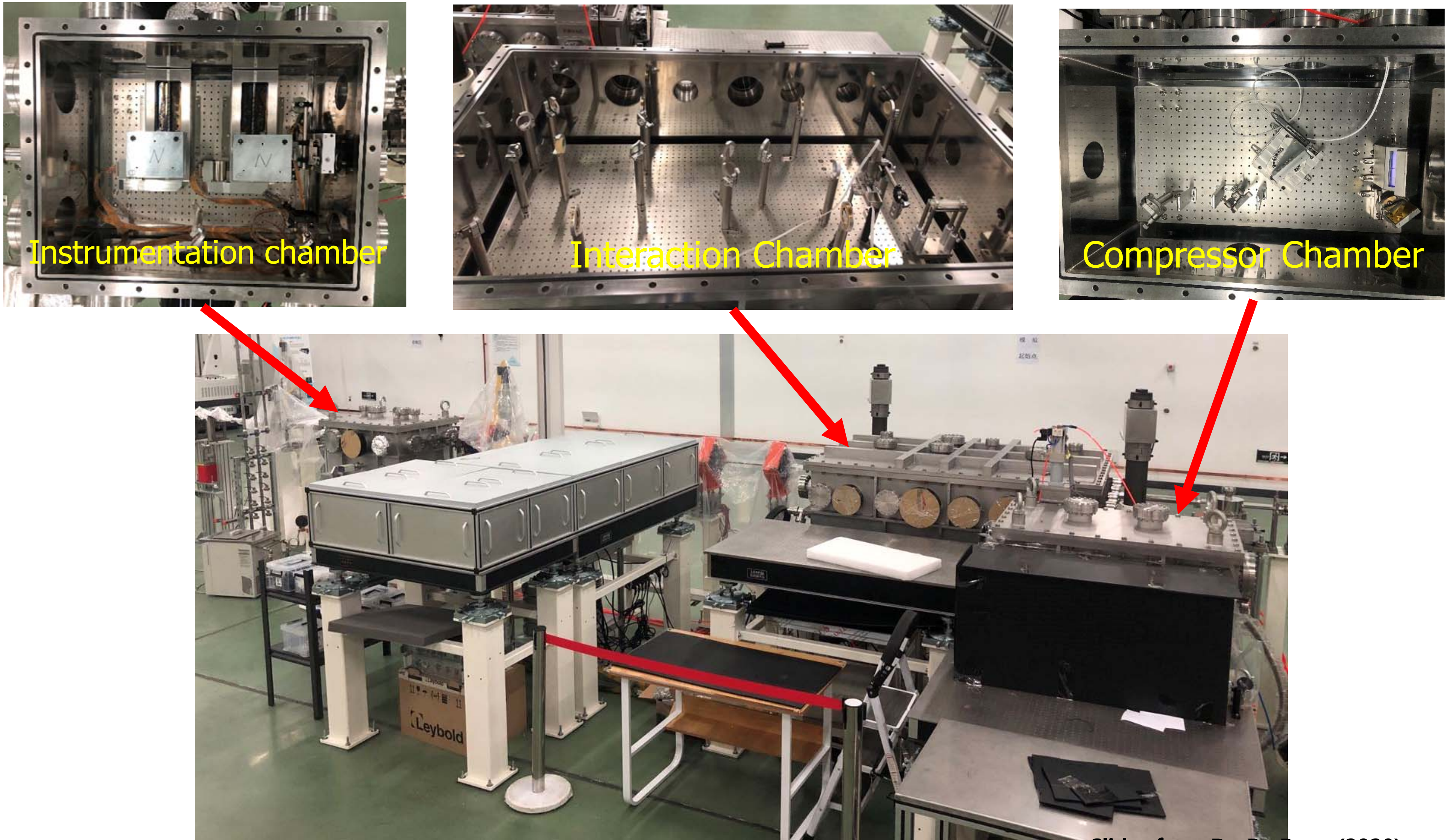
Pulse compressor efficiency: 72%

Pulse duration



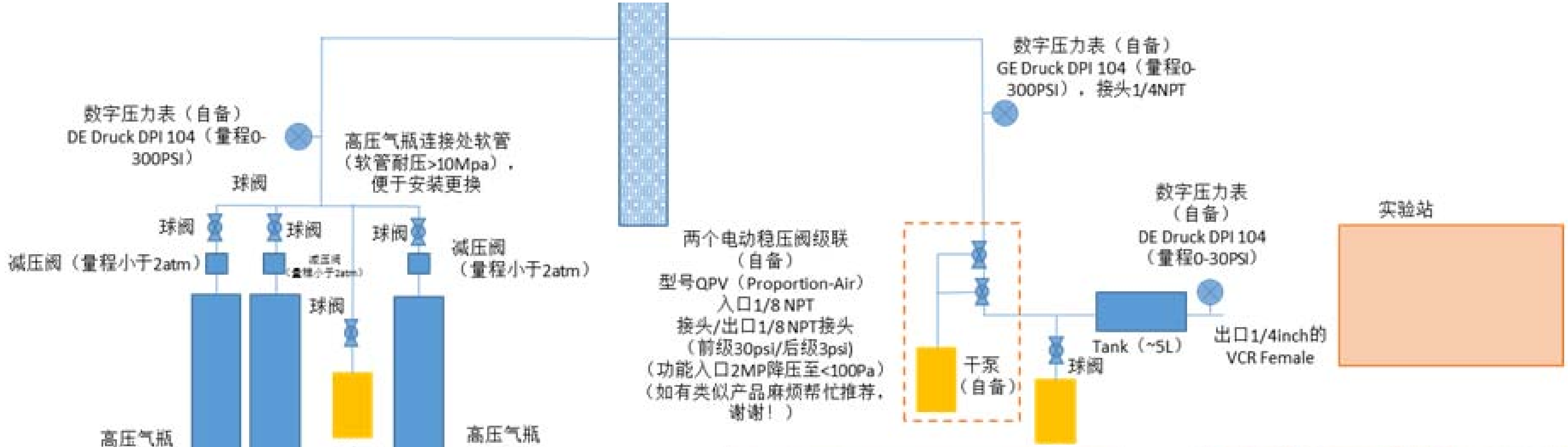
Slides from Dr. Bo Peng (2020)

Wait for the beamtime



Slides from Dr. Bo Peng (2020)

Experiment preparation → gas loop

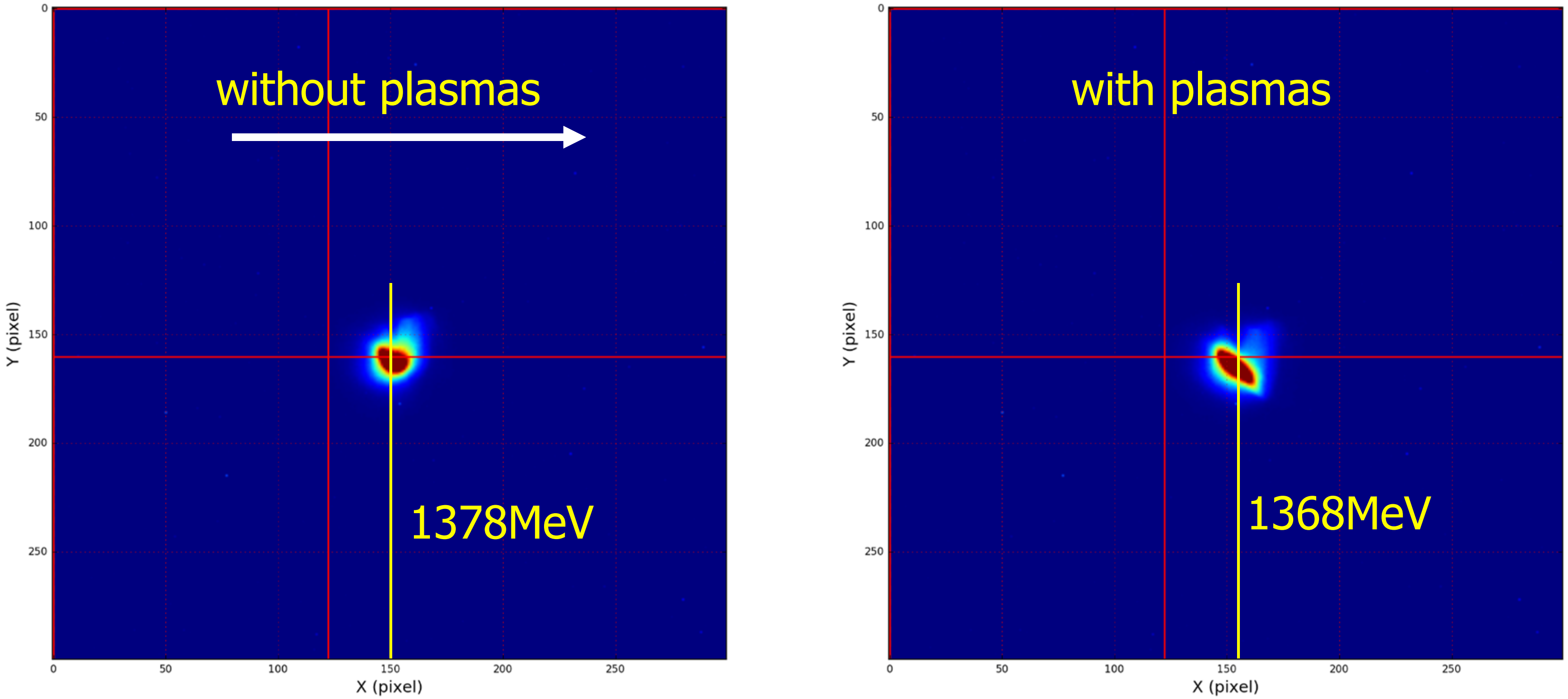


高压气瓶为混合气体（He：N2混合的摩尔比=90:10或者99:1）

Requirement:

200 ~ 10^5 pa (Negative pressure)

Preliminary experimental results



- ✓ Upgrade laser system, energy ~ 130mJ, pulse duration ~ 30 fs done
- ✓ Installation of light path, gas loop and diagnostic system done
- ✓ Laser and electron beam synchronization done
- ✓ Plasma dechirper experiment results, electron deceleration in plasmas (~ 10 MeV)

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

Hello Wei,

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

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.

Proposals will be reviewed tonight by SLAC group!!

Summary and prospects

- **Electron acceleration**
  - Start-to-end simulation is performed and single-parameter error analysis is presented
  - The asymptotic solution agrees well with the numerical solution and the PIC simulation results. Some damping mechanisms, such as ion motion, ion scattering, plasma temperature, betatron radiation, etc. are not considered in all these solutions.
  - The growth of hosing instability from statistical noise is acceptable when transformer ratio is 1-1.5, detailed error analysis for TR=1.5 is ongoing
  - There are powerful damping mechanisms in a real PWFA. TR≥3 is still alive
- **Positron acceleration**
  - Asymmetry beam scheme is well accepted, more schemes are studied
- **Experiments affected by COVID-19, but recovered now**
  - 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, also no clear timetable. However, we are on an unexplored path instead of a "me too" path. Keep going is more important than a clear timetable.**

Thank you!