Recent Progress on CEPC Plasma Injector

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

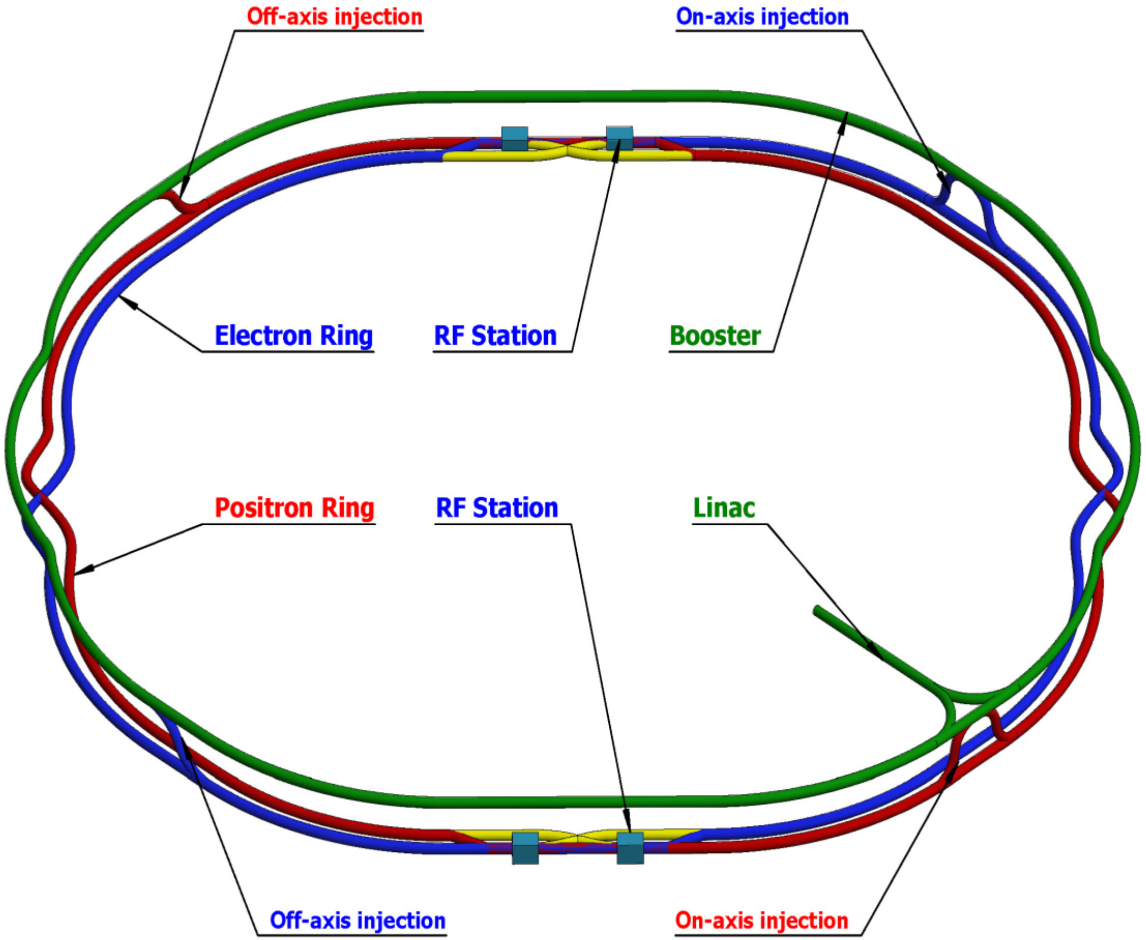
On behalf of the IHEP-THU-BNU AARG team

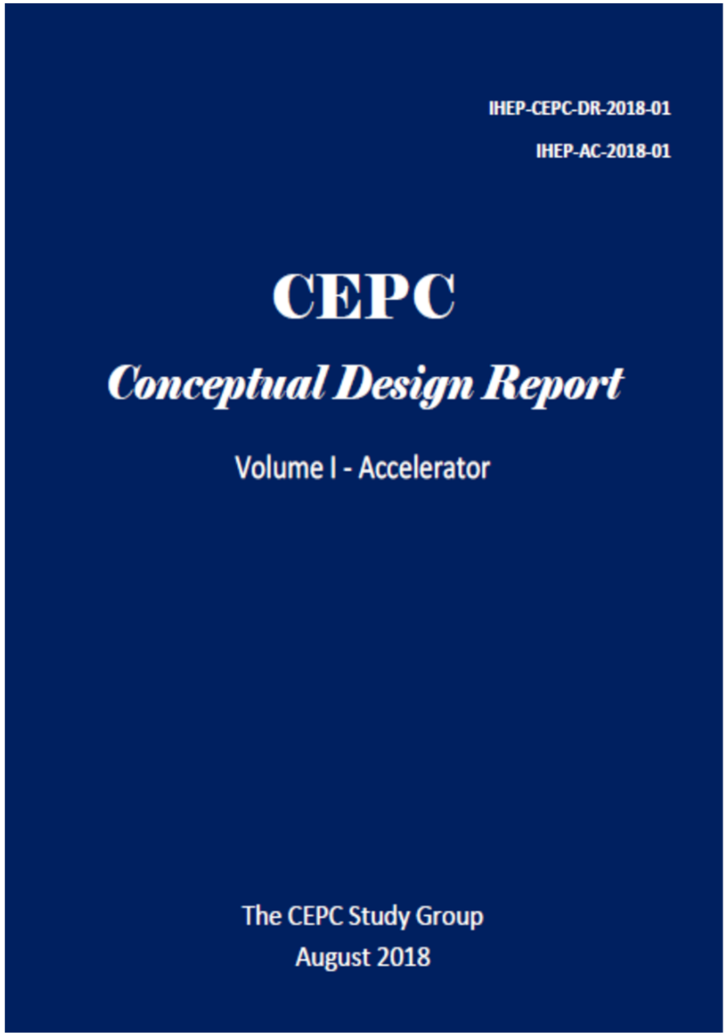
Oct. 13, 2021

Outlines

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

Circular Electron Positron Collider





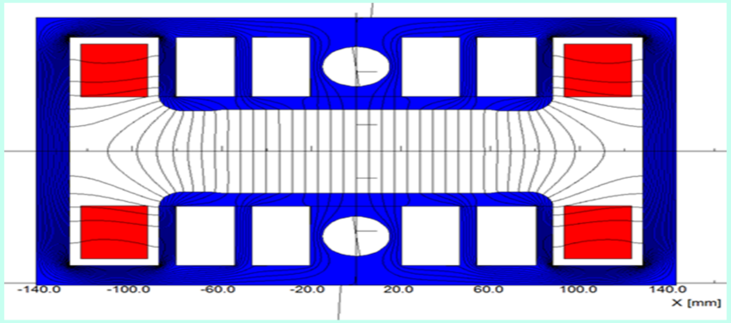
CDR (Acc.) International Review @ 2018.6.28-6.30 & Final Released @ 2018.9.2

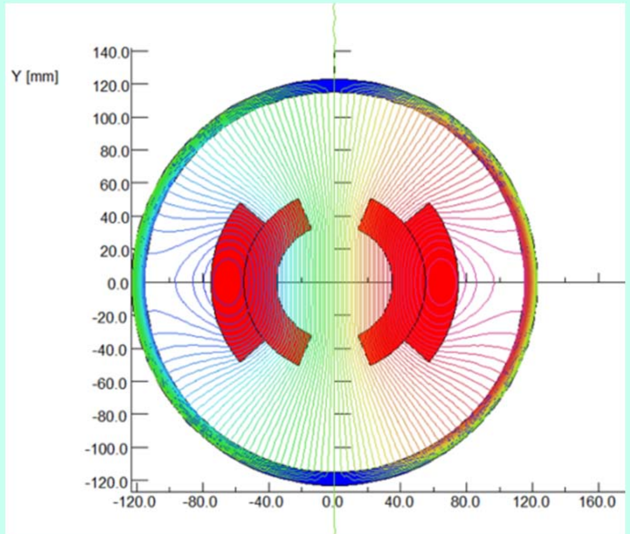
Low field Dipole Problem in Booster

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

- 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.

Without magnetic core
(Twice excitation current)

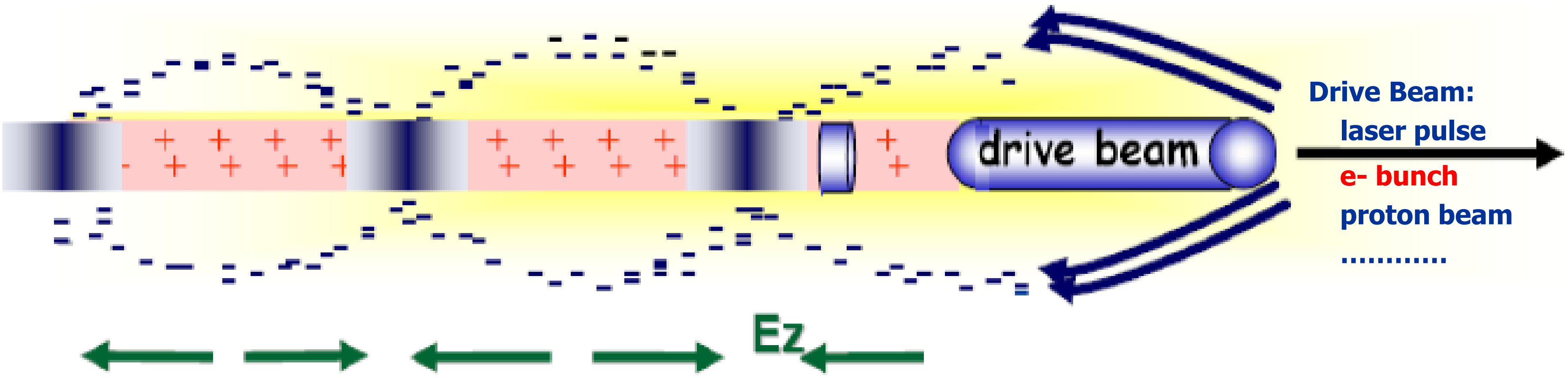




➢ Thinking beyond CDR

- 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)

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

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

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,
  - 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

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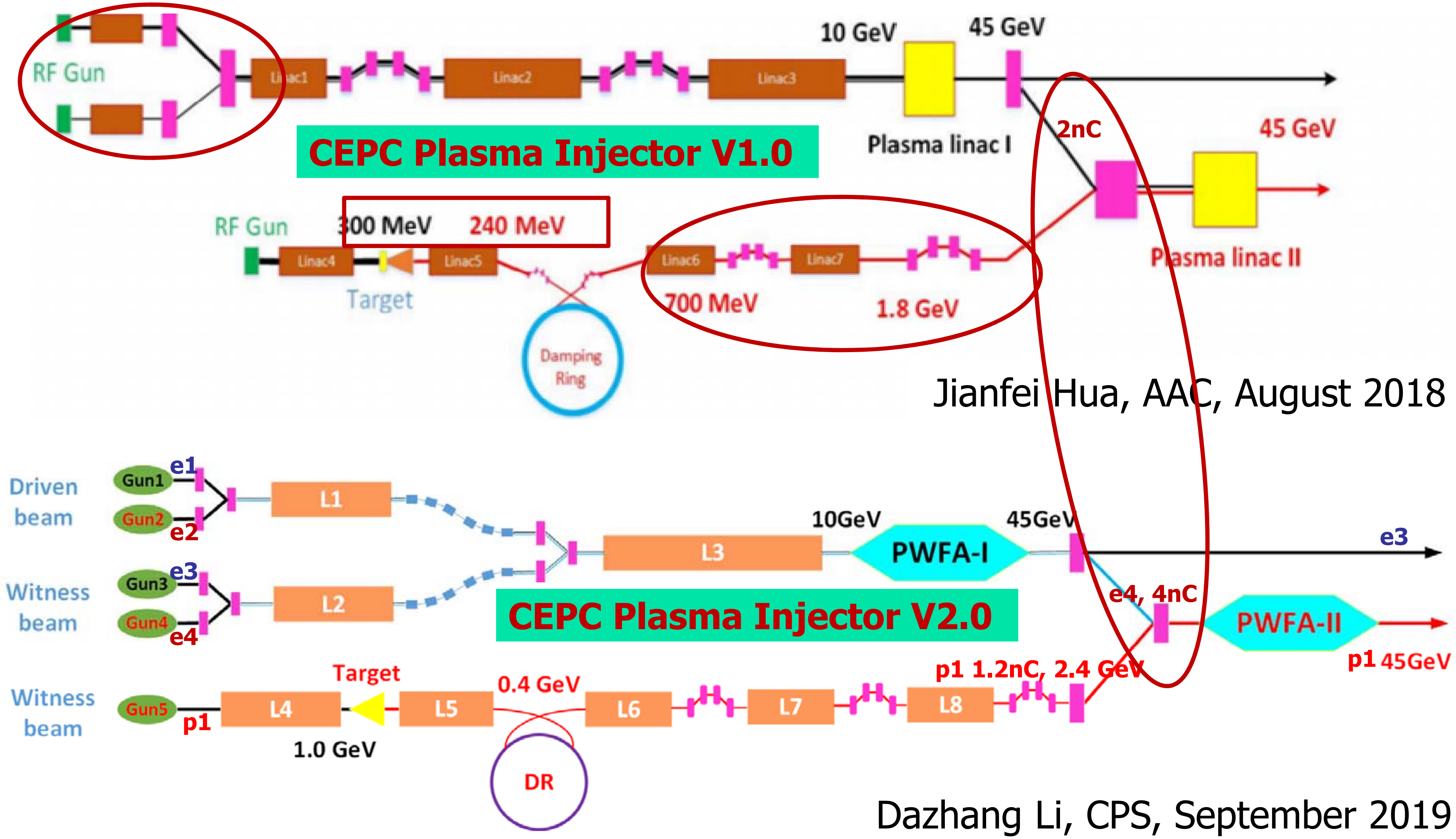
CPI conceptual Design V1.0→V2.0



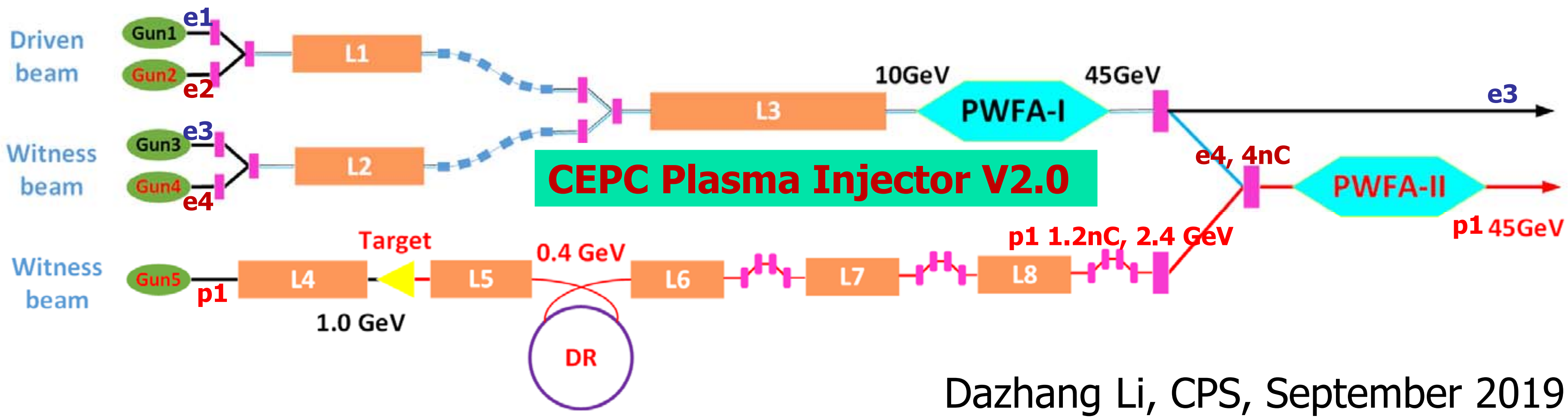
Jianfei Hua, AAC, August 2018

Dazhang Li, CPS, September 2019

Requirement & Key issues of CPI

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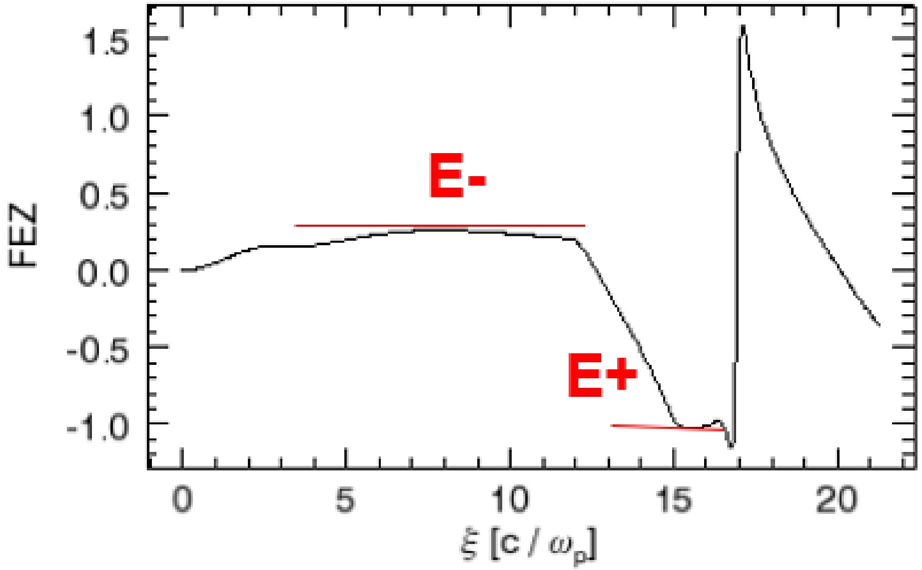
What is High Transformer Ratio?



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

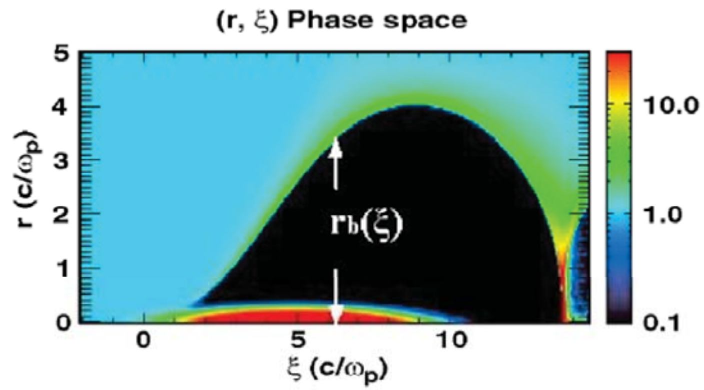
$$TR = \frac{\bar{\gamma}_{trailer} - \gamma_{trailer\_initial}}{\bar{\gamma}_{driver} - \gamma_{driver\_initial}}$$

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

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

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

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

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

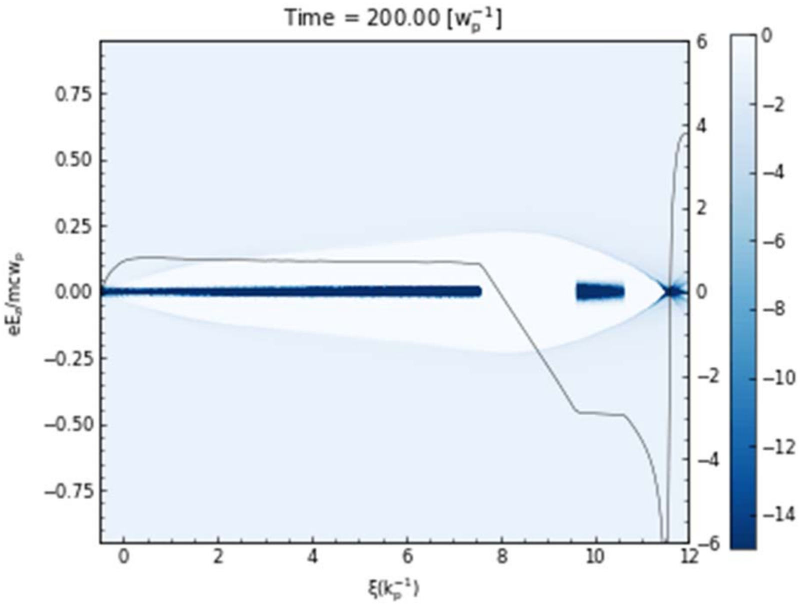
HTR mode, R ≥ (45.5-10)/10=3.55

Low TR mode, R ≥ (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

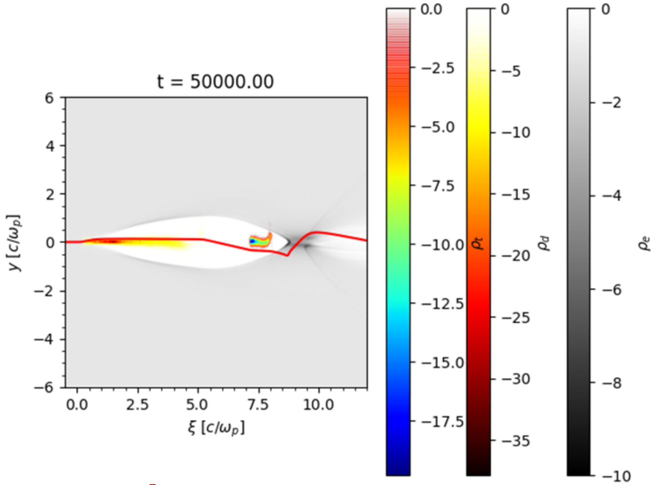
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

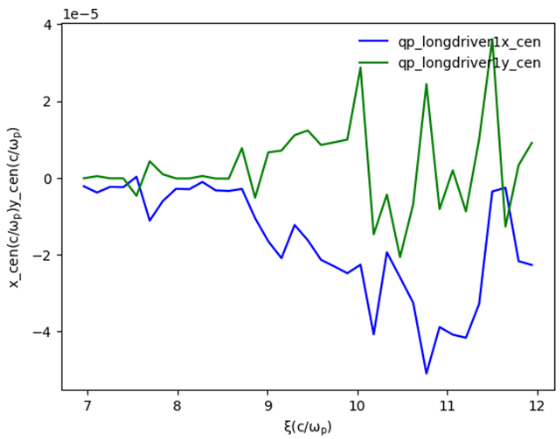
Error analysis → not fully symmetry

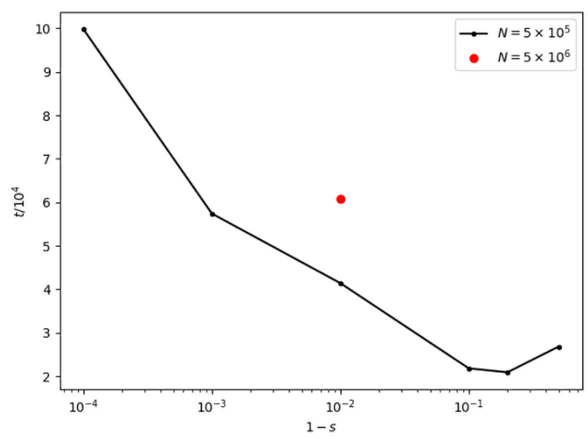
In the QuickPIC simulation, if the drive beam is not fully symmetry, even let <x_d> = 0, the hosing instability occurs much earlier than we expect. For example, adding only **0.025nm** slice jitter to drive beam leads to severe hosing instability. Actually, the resolution of the simulation box is about 2 μm, which is much larger the added noise. **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
- Partial particles asymmetry → hosing improved



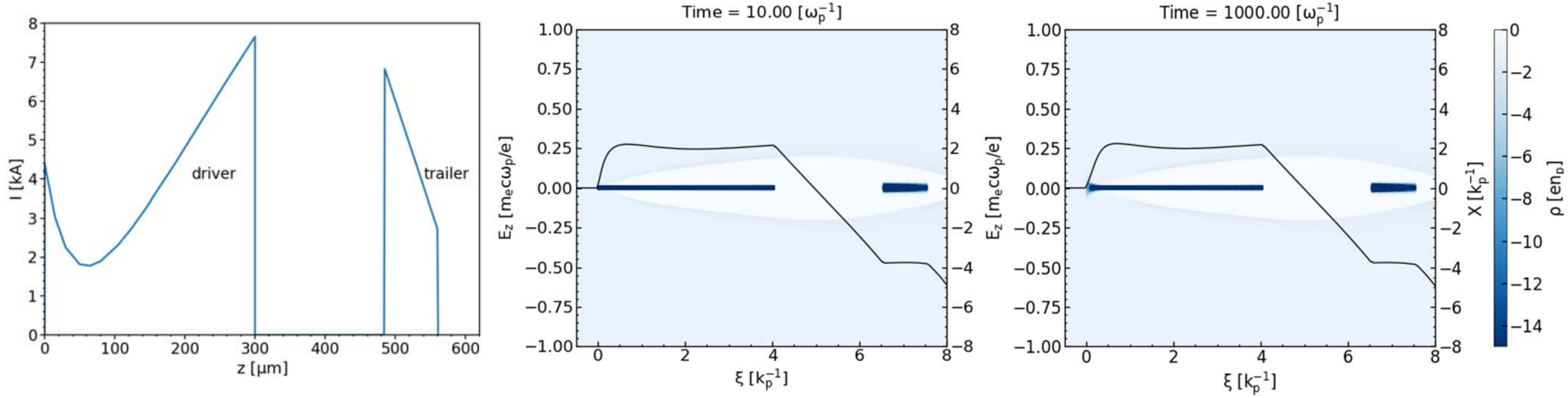




5×10^5 particles 99.99% symmetry $\sigma_z \sim 5$ lose 50% particles at 100000 w_p^{-1}

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	

	TR ~ 4	TR ~ 1.6
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	>3.55	>1.5
Efficiency(%) (driver -> trailer)	60.0	54.0

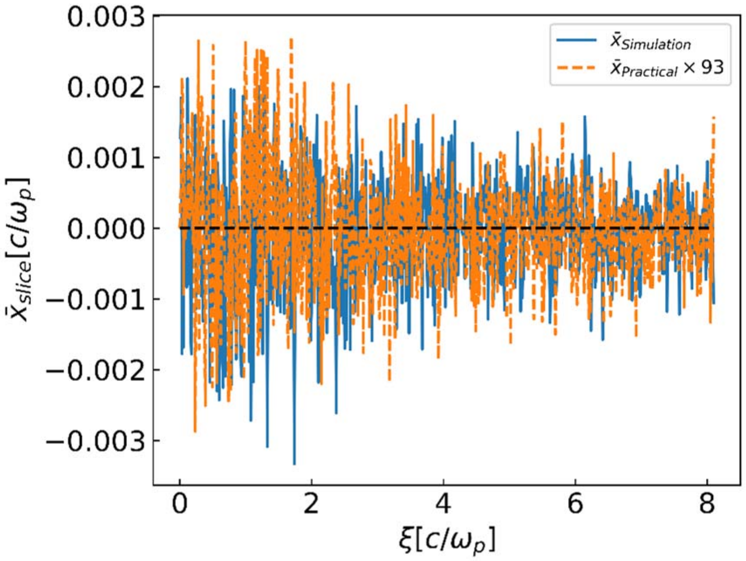
Slide from Dr. X. N. Wang, Dr. S. Y. Zhou and Prof. W. M. An (2021)

Initial noise macro vs. practical

- 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.



Hosing instability in bubble regime

- A straightforward way to calculate the asymptotic solution.
  - For the most basic equations

$$\frac{\partial^2 x_b}{\partial s^2} + x_b = k_\beta^2 x_c$$

$$\frac{\partial^2 x_c}{\partial \xi^2} + \omega_0^2 x_c = \omega_0^2 x_b$$

  - With the short pulse, long range limit, we can assume

$$x_b = \bar{x}_b e^{ik_\beta s}$$

$$x_c = \bar{x}_c e^{ik_\beta s}$$

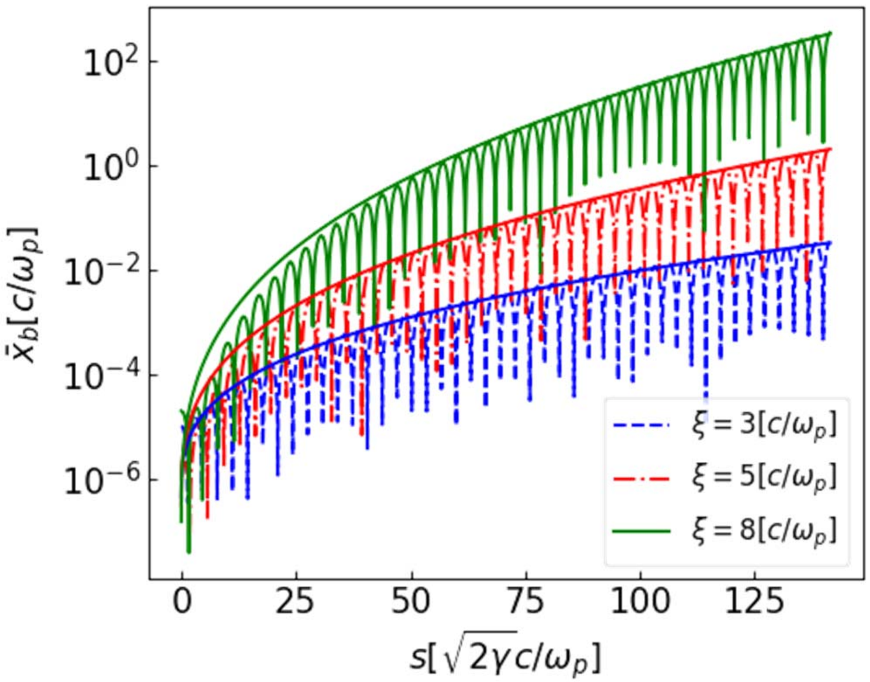
  - Under this limit, $\partial_s \ll k_\beta, \partial_\xi \gg \omega_0$, and we have

$$2ik_\beta \partial_s \bar{x}_b = k_\beta^2 \bar{x}_c$$

$$\partial_\xi^2 \bar{x}_c = \omega_0^2 \bar{x}_b$$

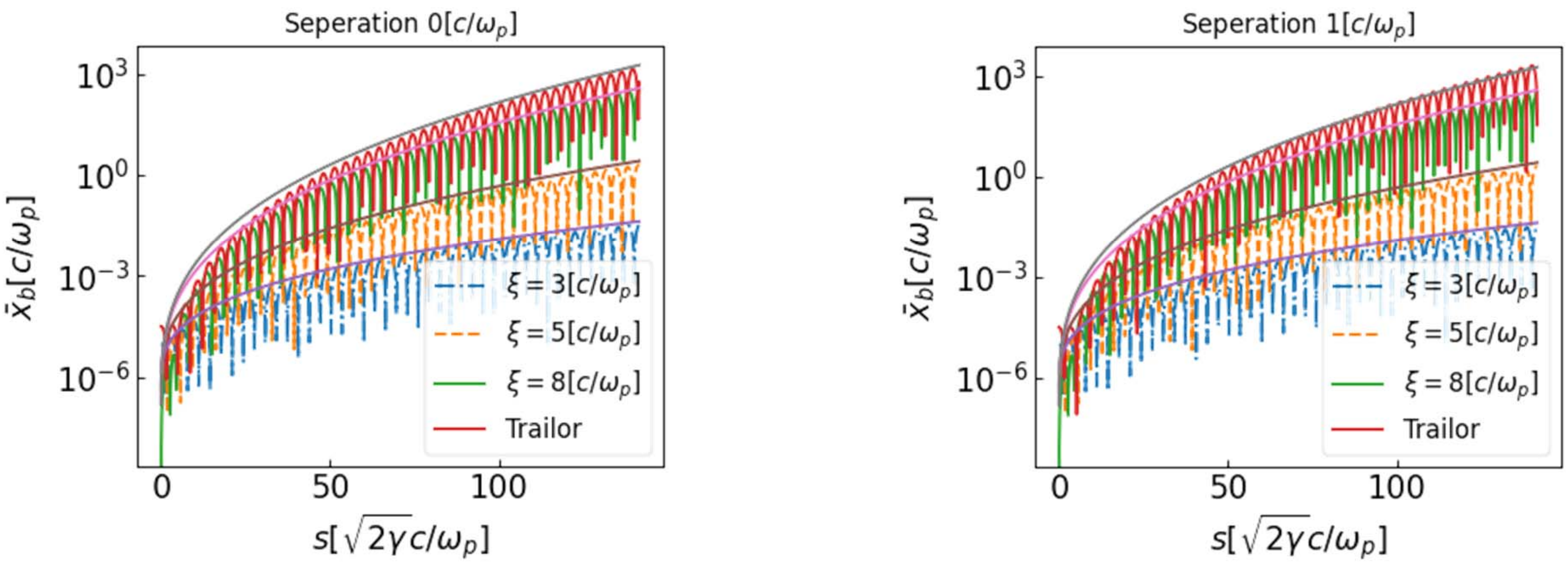
  - Let $\bar{x} = Ae^{\gamma_0 (k_\beta s)^m (\omega_0 \xi)^n}$

$$\partial_\xi^2 \partial_s \bar{x}_b = \frac{\omega_0^2 k_\beta^2}{2ik_\beta} \bar{x}_b$$



C. Huang, W. Lu et al., PRL **99,** 255001 (2007)

Witness beam's hosing instability

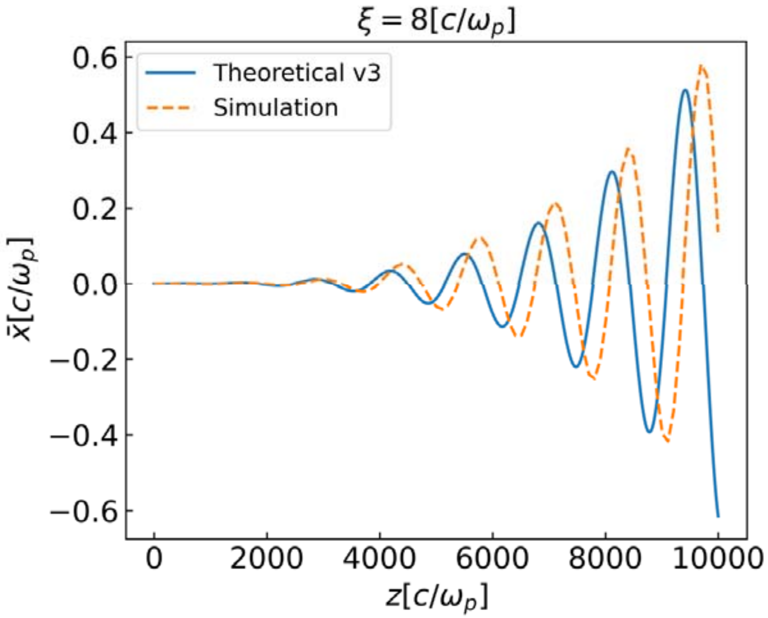


Different separation has little effects on hosing growth. Which means bunch train may not effective for damping hosing instability

PIC results Vs. Numerical solution

- Take the c_r, c_ψ into consideration
- Other damping regime, such as the energy spread, nonlinear focusing force can be quantified by the damping of x_b
- $\frac{\partial^2 x_c}{\partial \xi^2} + c_r c_\psi \omega_0^2 x_c = c_r c_\psi \omega_0^2 c_b x_b$

c_r, c_ψ from simulation
$c_b = 0.8$



The asymptotic solution agrees well with the PIC simulation result

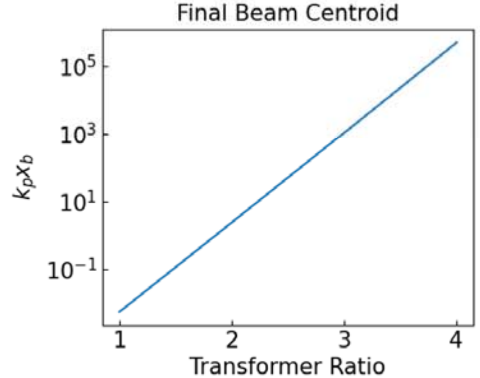
Transformer Ratio limitation

- 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 $k_p s \sim \gamma_0 R$

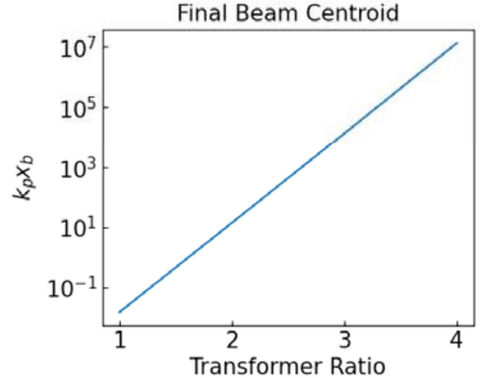
➢ We can obtain the final beam centroid of the witness beam at the end of the acceleration

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

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

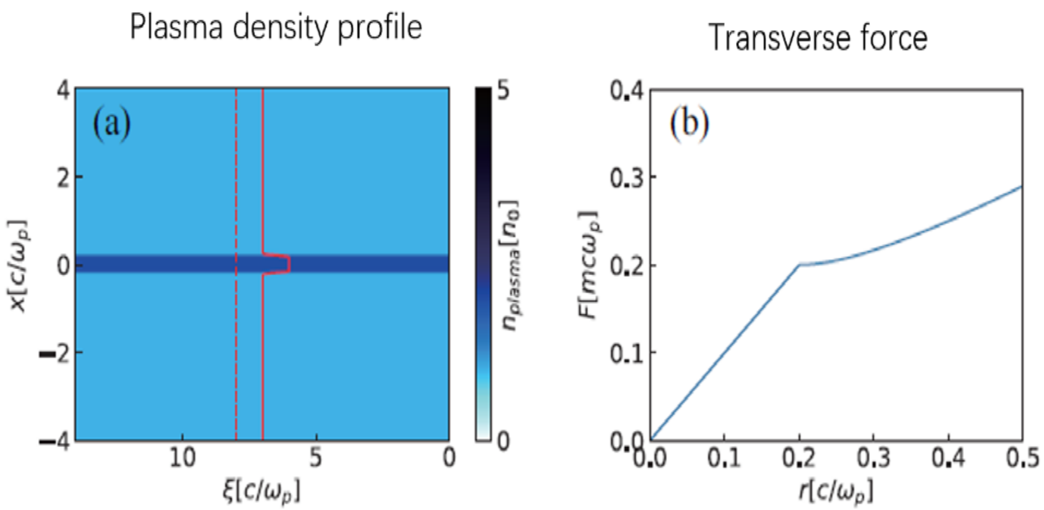


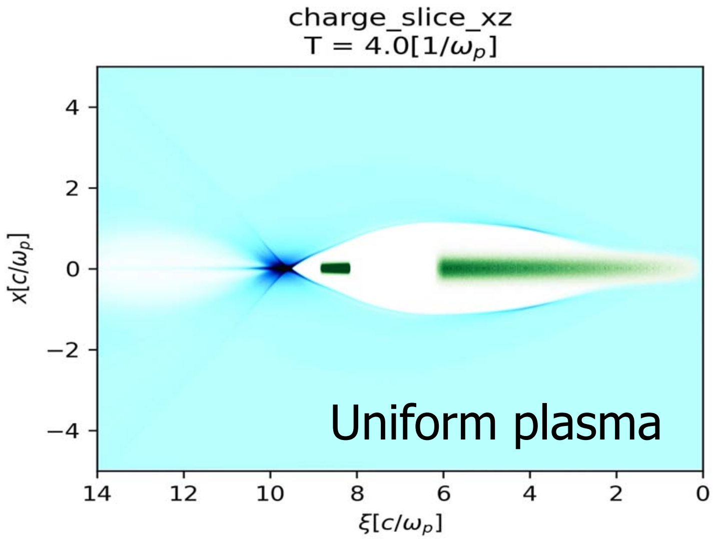
➢ For a 20GeV driver, beam size $k_p\sigma_r = 0.2$, c=0.7, $c_b = 0.8$



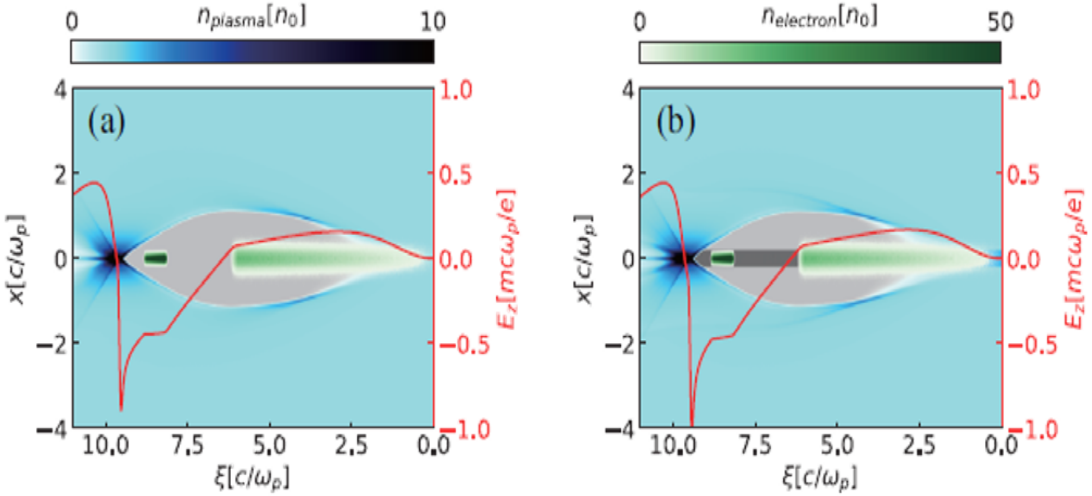
Transformer ratio 1-1.5 is acceptable without extra damping regime

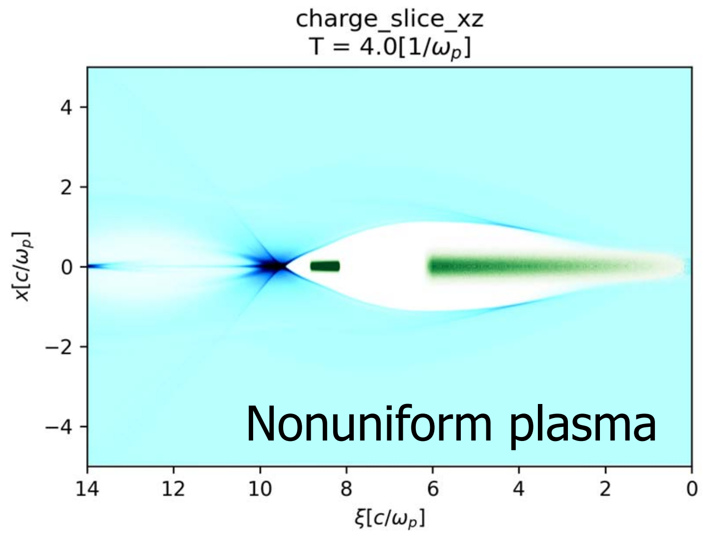
One powerful damping method



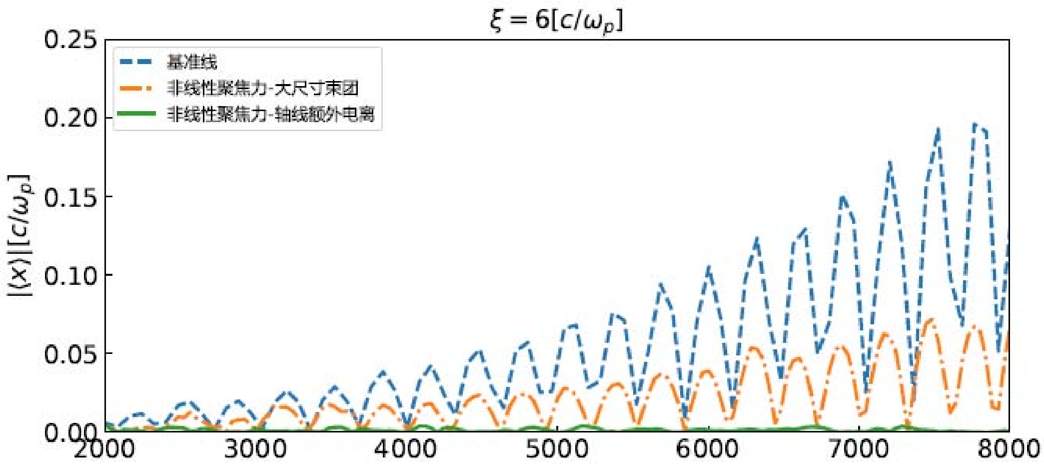


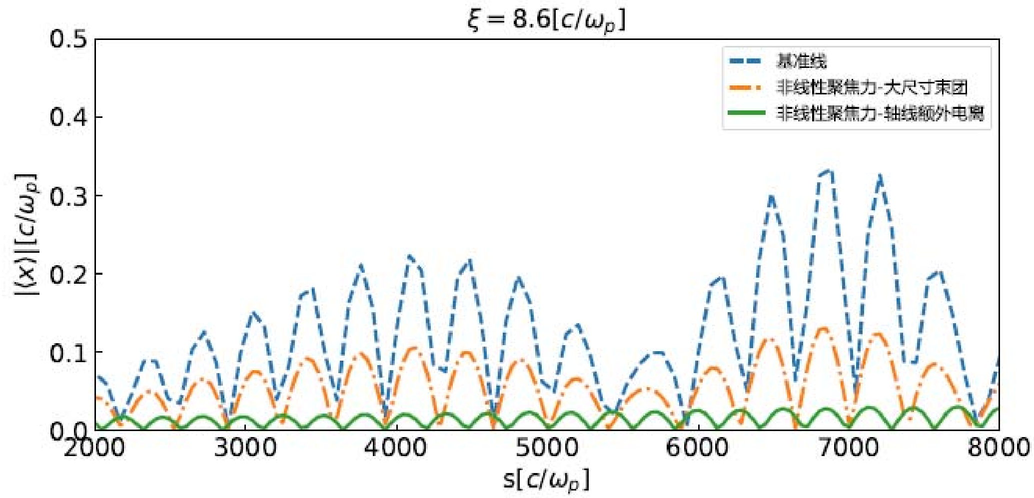
Little effects on Ez field



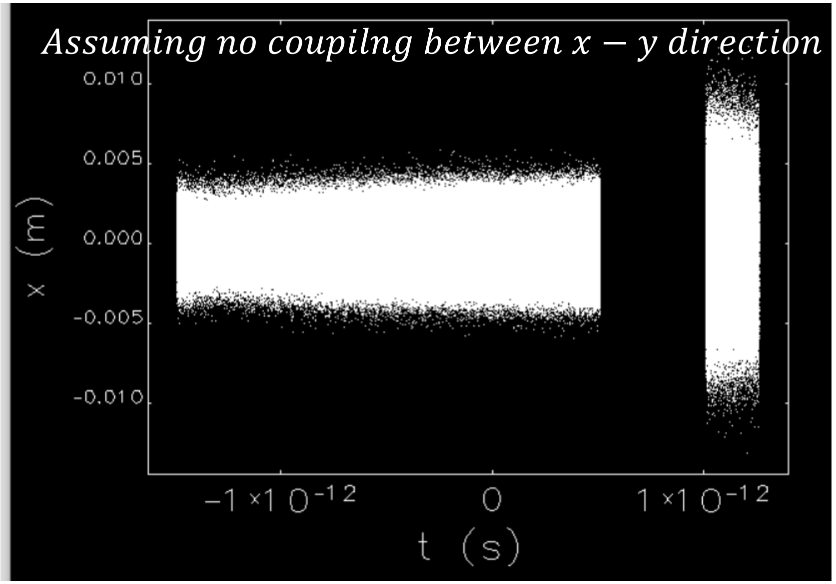


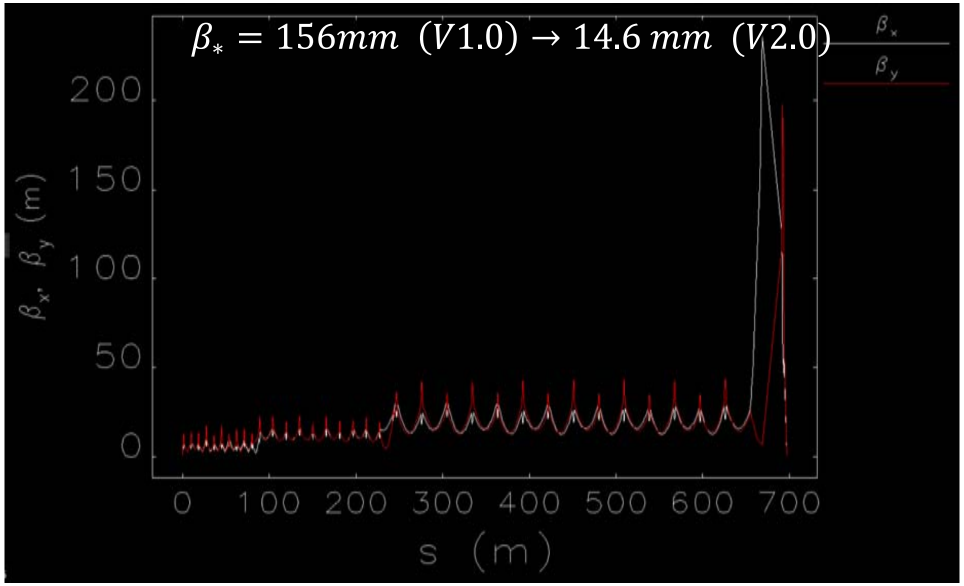
One powerful damping method

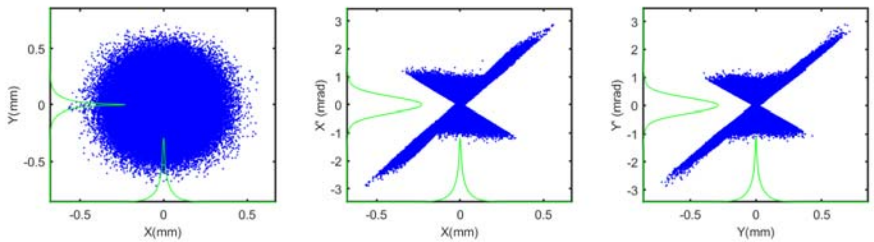


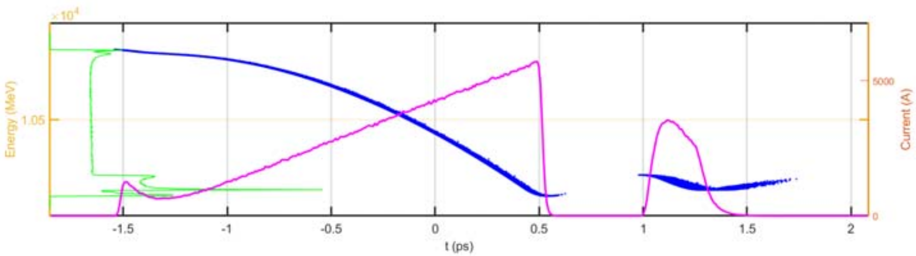


Linac optimization for ideal beams









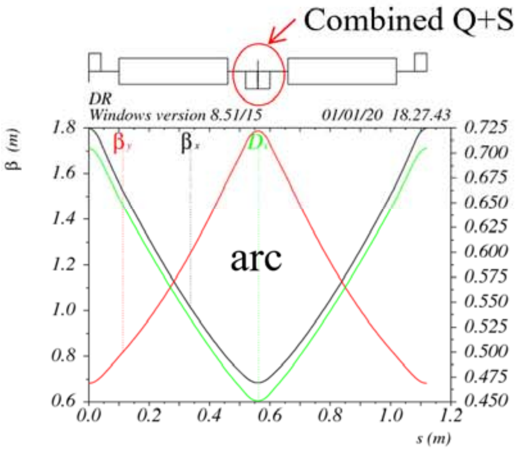
L-band photocathode rf gun under design.

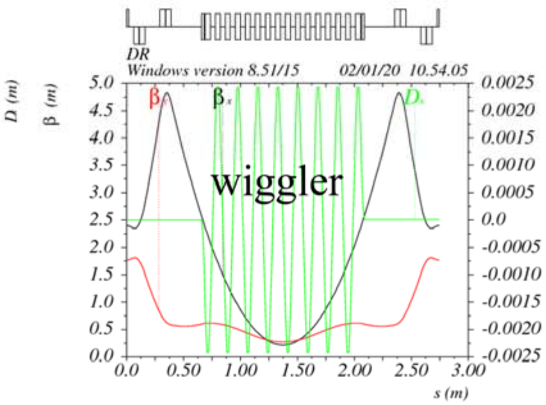
Finished the preliminary linac design and the end-to-end simulation (e- gun → FFS). Beam distribution improved but can not meet the requirements yet.

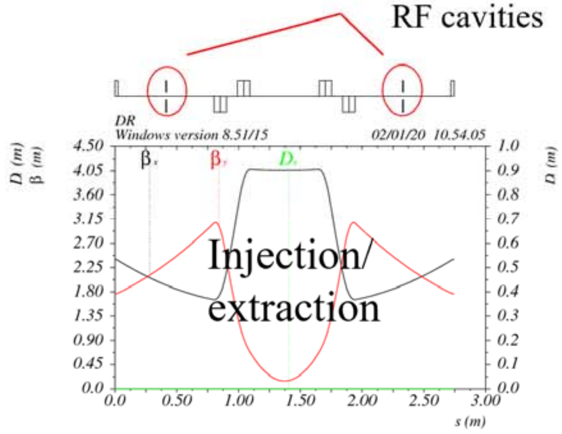
NEED MORE OPTIMIZATIONS

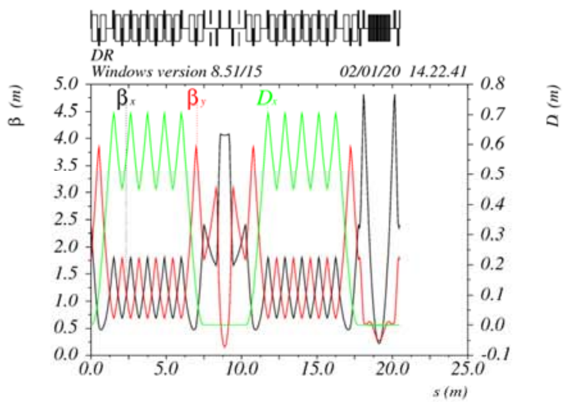
By Dr. Cai Meng & Guan Shu rom IHEP (2020)

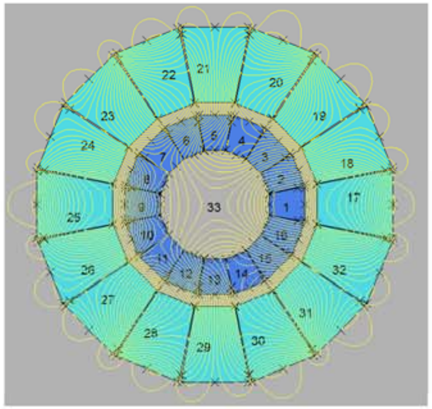
Damping Ring Optics Design V3.0

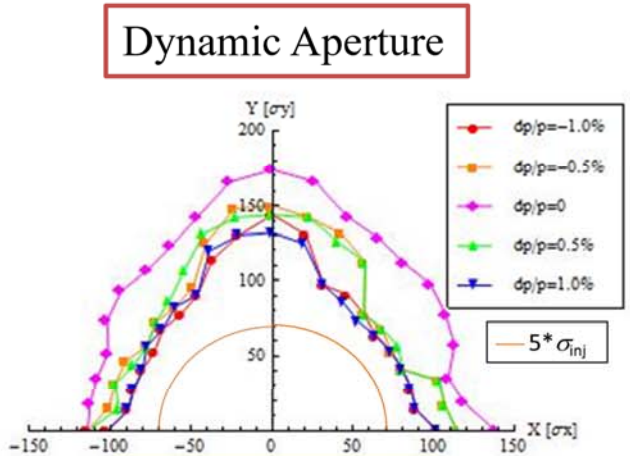












$\nu_x / \nu_y = 3.16/3.21$

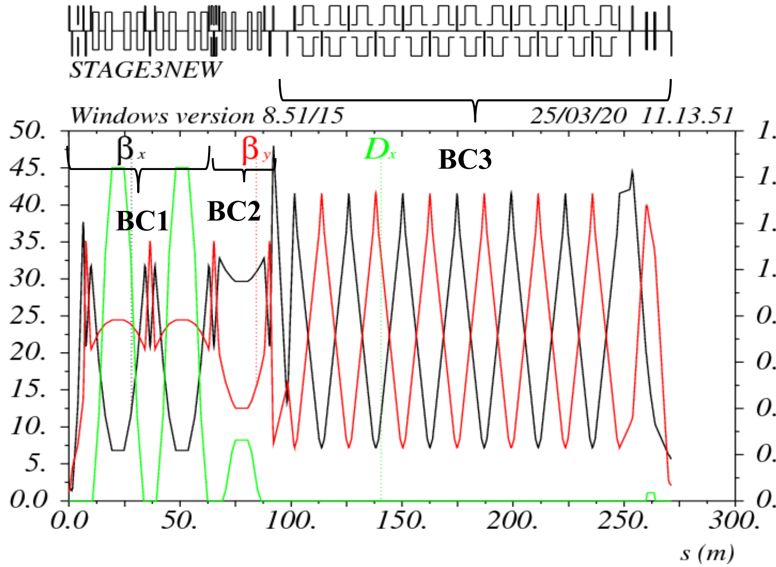
- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

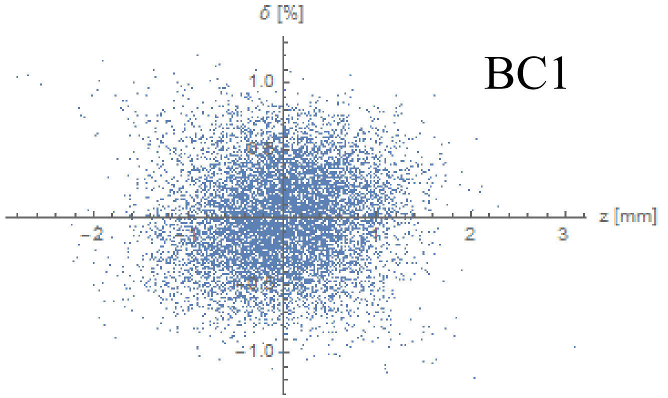
By Dr. Dou Wang and Cai Meng from IHEP (2020)

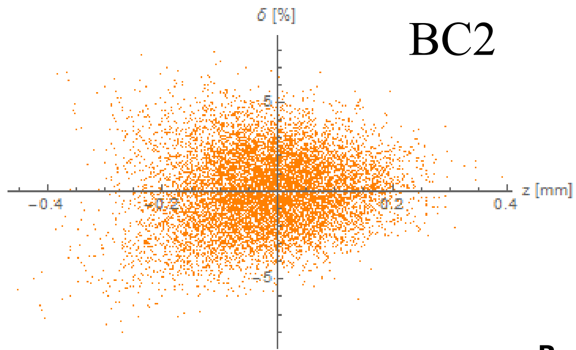
3-Stage Bunch Compressor

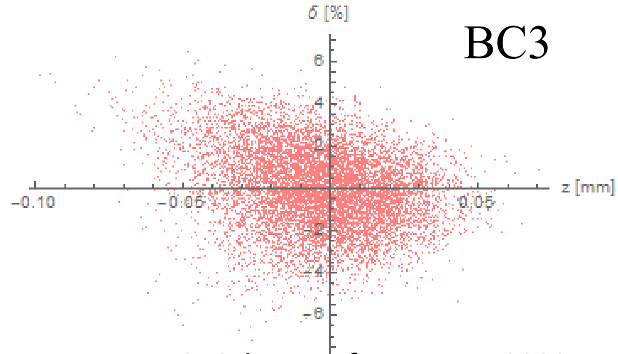
	BCI	BCII	BCIII
Initial energy (MeV)	400	400.1	405
δinj (%)	0.05	0.367	2.17
Initial σz (mm)	4.4	600	100
f_{RF} (GHz)	2.860	5.712	5.712
Voltage(GV)	0.0056	0.12	4.18
Gradient (MV/m)	20	40	40
L (m)	0.28	3	104
ϕ_{RF} (degree)	89	88	61.5
R_{56} (mm)	1200	27.6	5.5
Final energy(MeV)	400.1	405	2400
δext (%)	0.367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







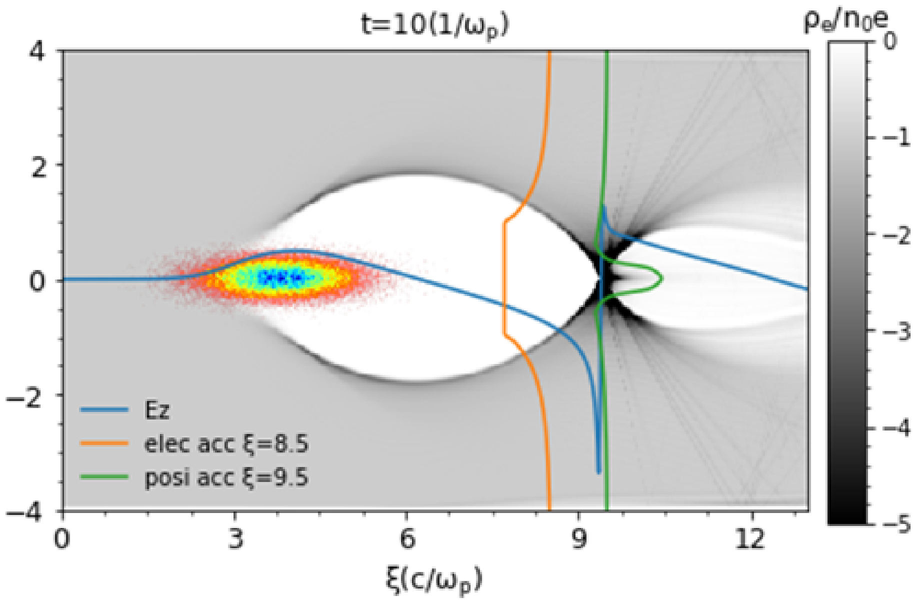


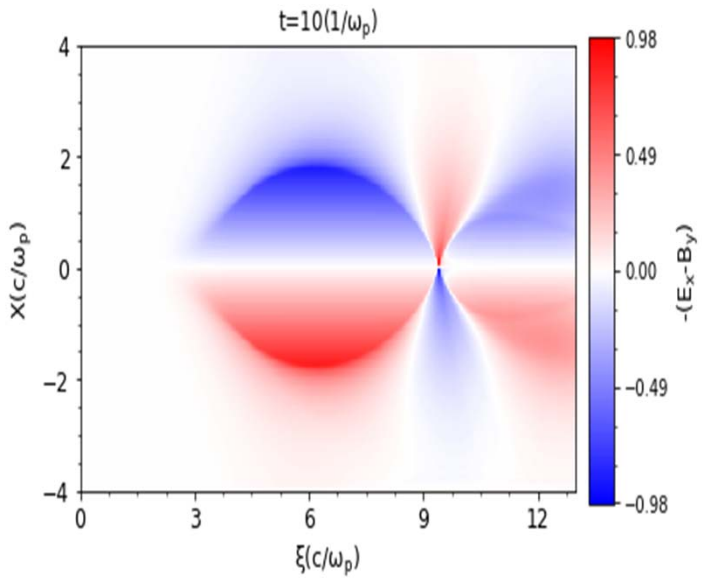
By Dr. Dou Wang & Cai Meng from IHEP (2020)

Basic ideas for improving e+ acc.

A "perfect" wakefield means:

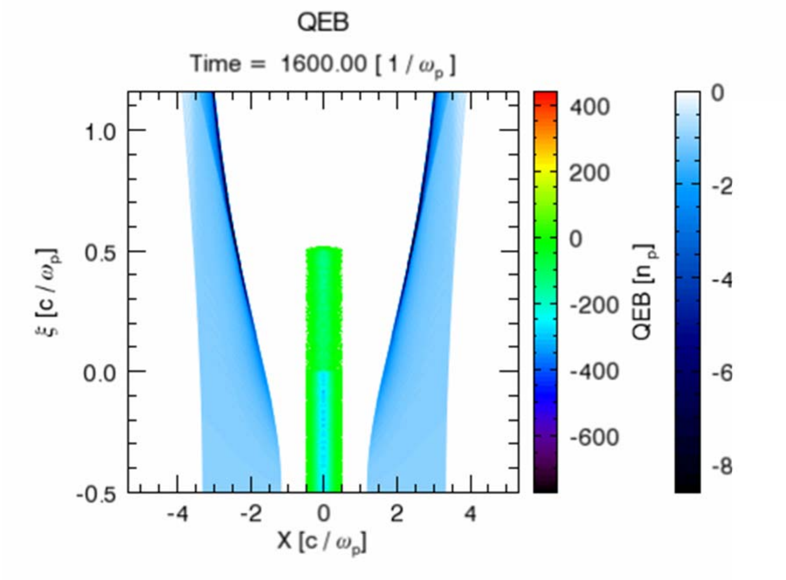
- **Flat longitudinal wakefield, particles at different position experience same Ez**
- **Transverse wakefield can provide focusing forces to the accelerated particles**

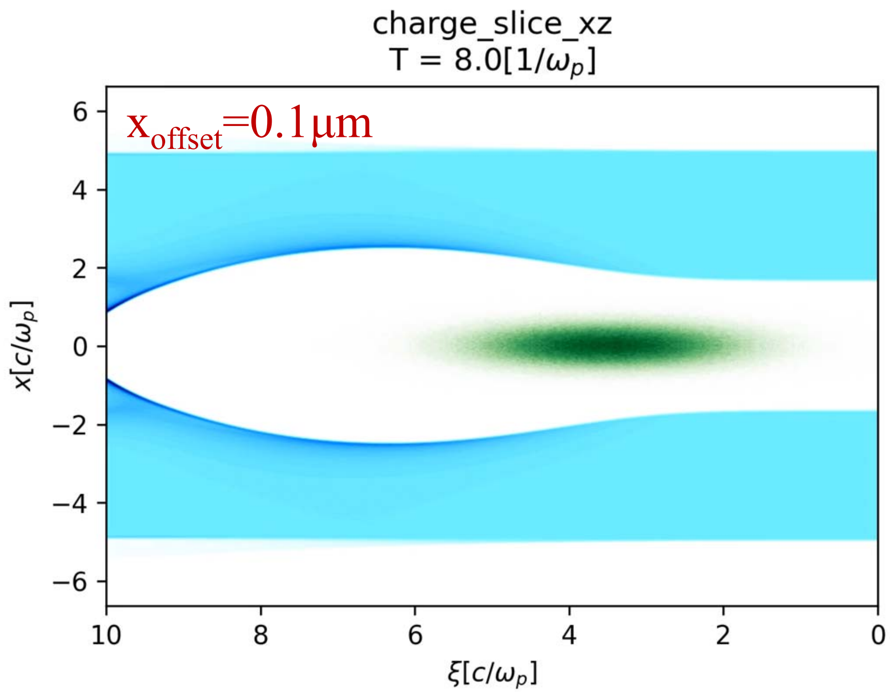




So, the blowout wakefield in uniform plasmas is quite fit for e- acceleration, while unfit for e+ acceleration

Baseline method → not very practical

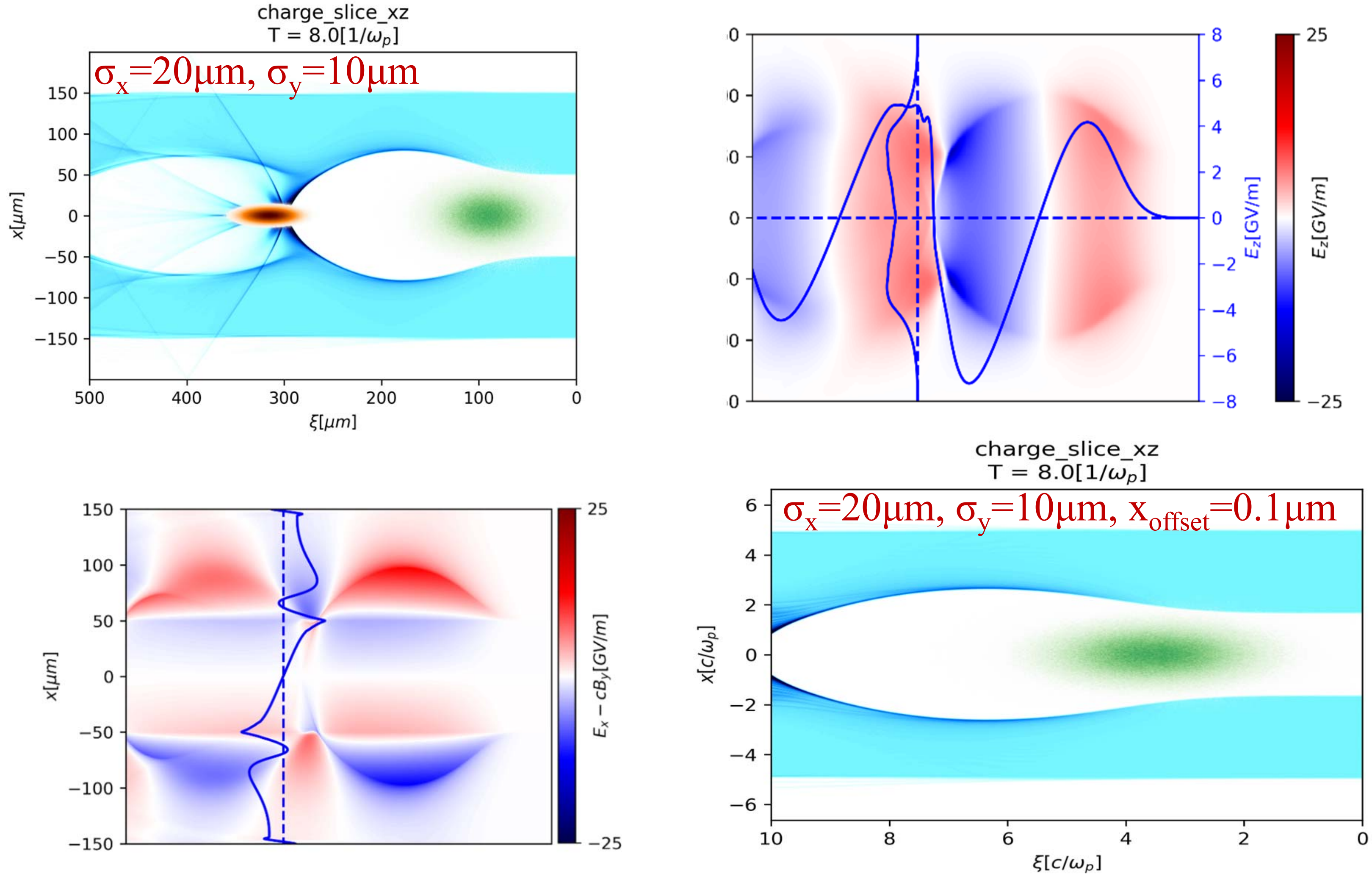




- **High efficiency 60%**
- **Low energy spread ~0.5%**
- **Small emittance growth**
- **Need e- driver, e+ trailer and plasma channel coaxial, not very practical**

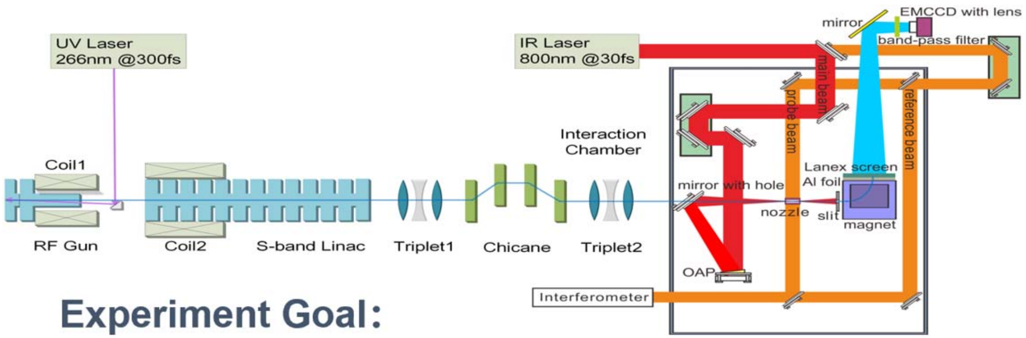
Simulation performed by THU team in 2018, based on the hollow channel idea *[S. Gessner et al., Nat. Commun. 7, 11785 (2016)]*

Modified design → asymmetry driver



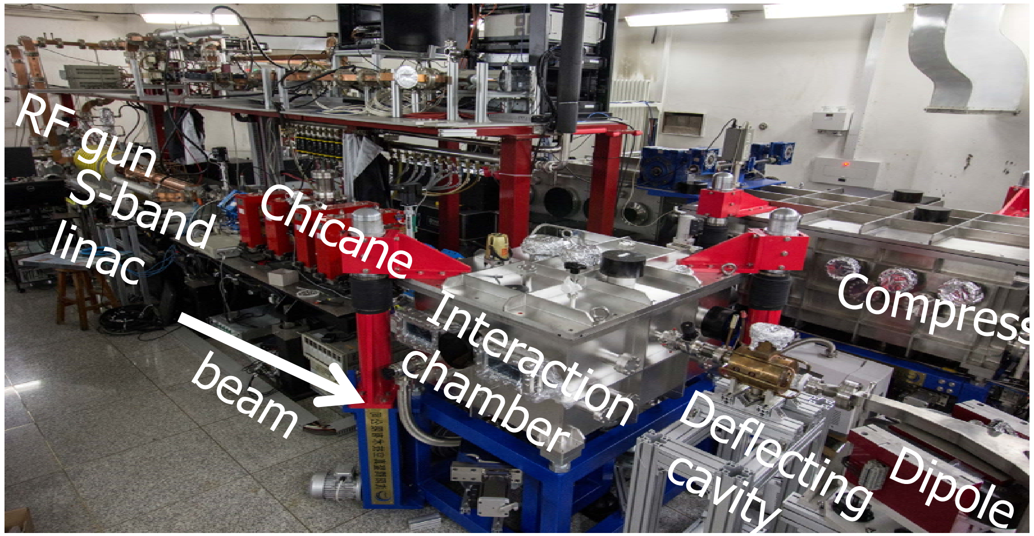
S. Y. Zhou, W. Lu, et al., Accepted by PRL, editor suggestion

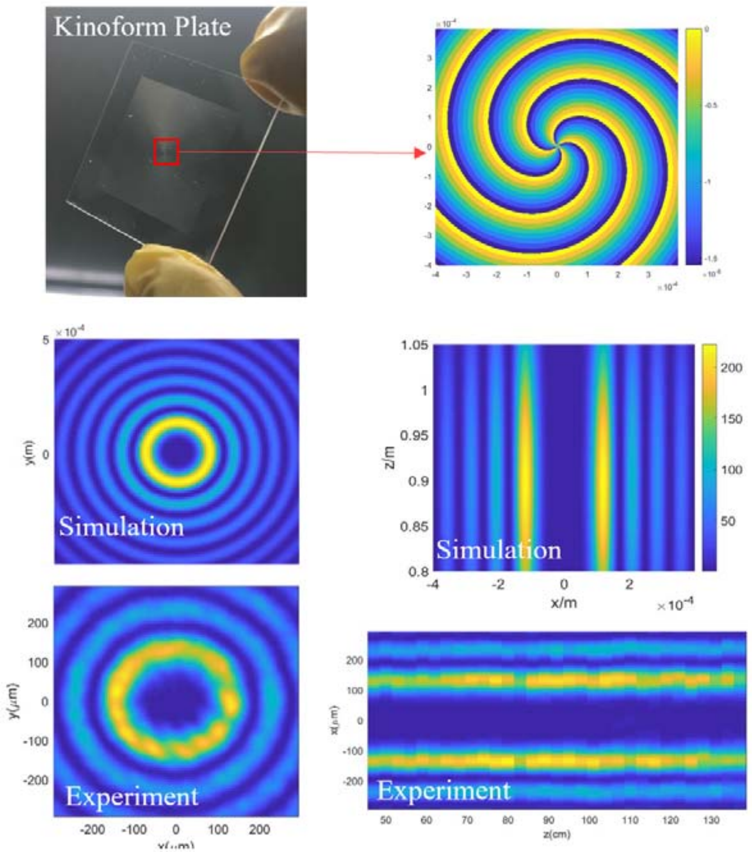
Plasma dechirper experiment @ THU



Experiment Goal:

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

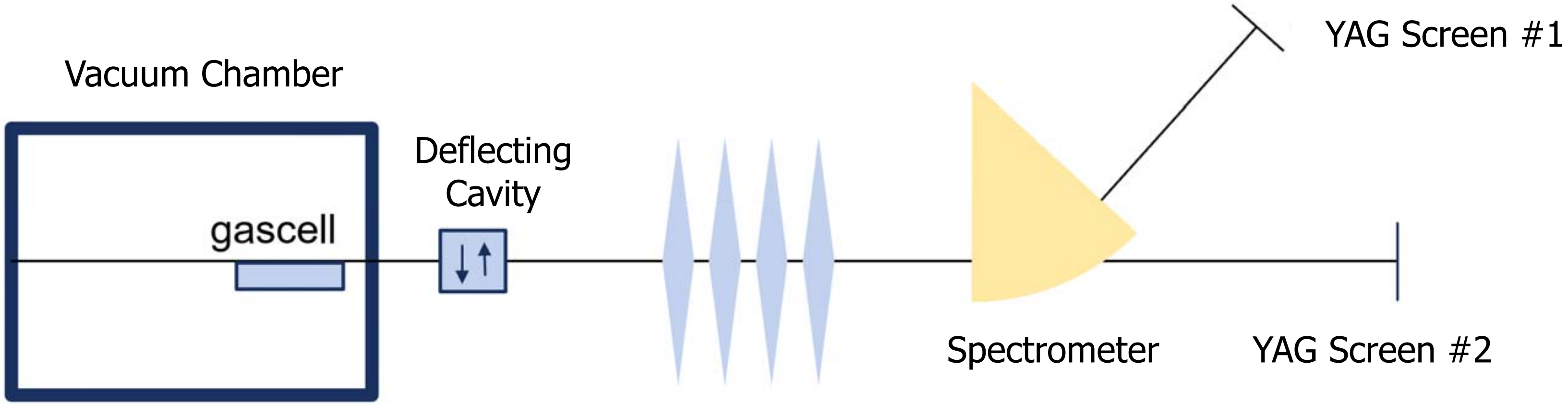


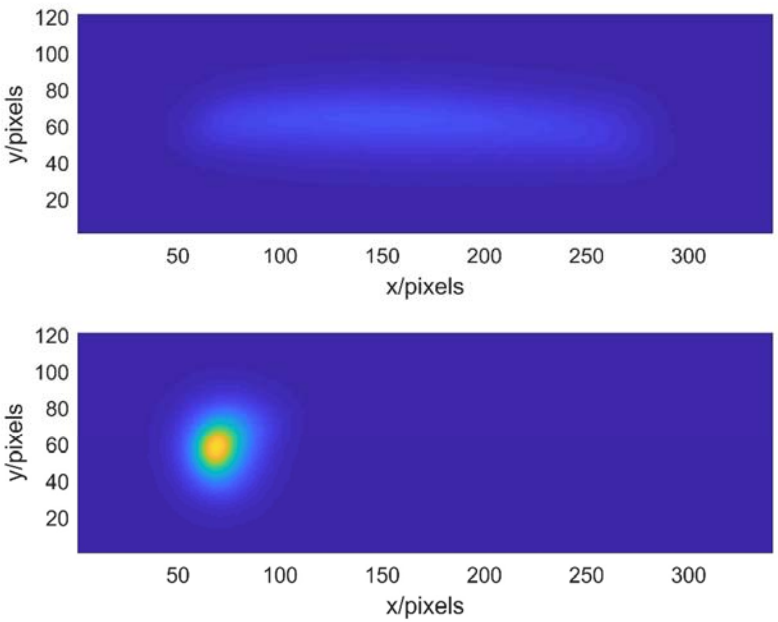


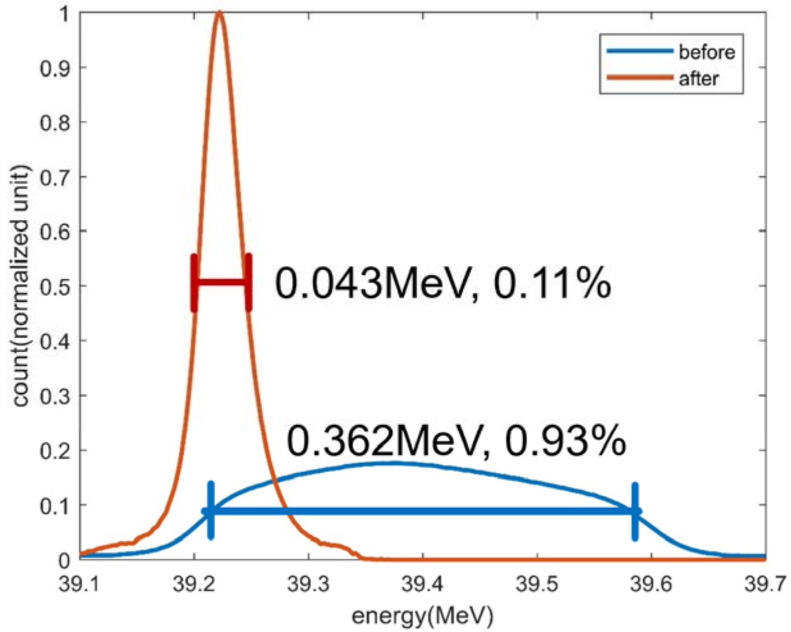
Planned to finish it before February, but delayed by COVID-19.
Re-started in Oct. 2020

Slides from Dr. Shuang Liu (2020)

Energy spread from 1% to 0.1%





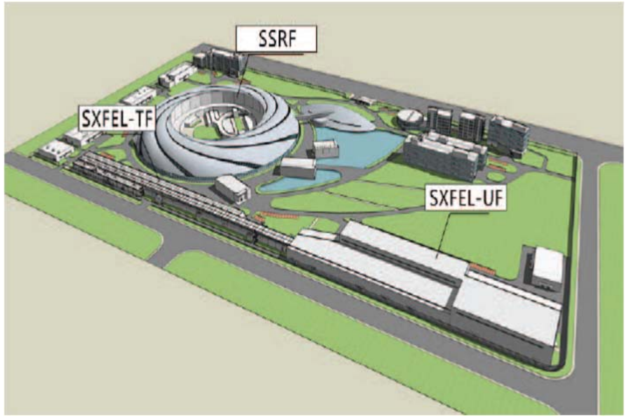


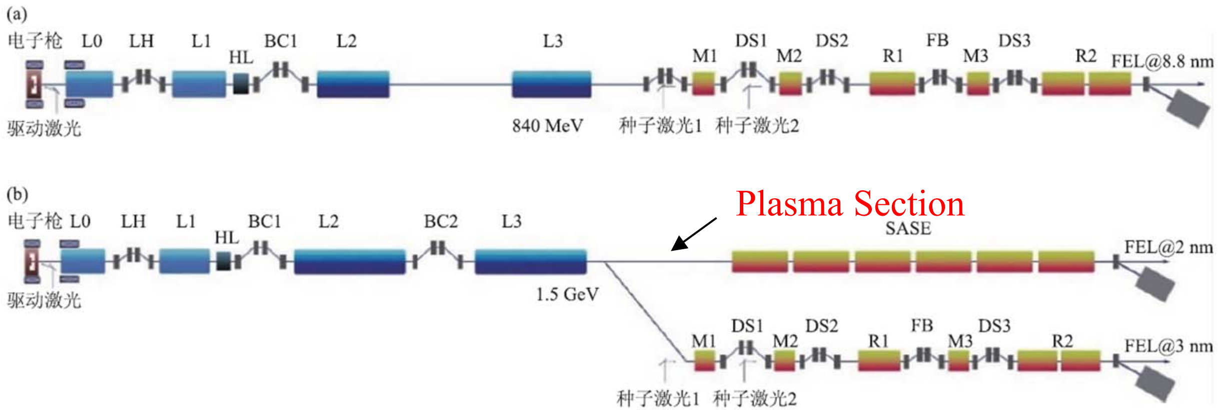
Slides from Dr. Shuang Liu (2020)

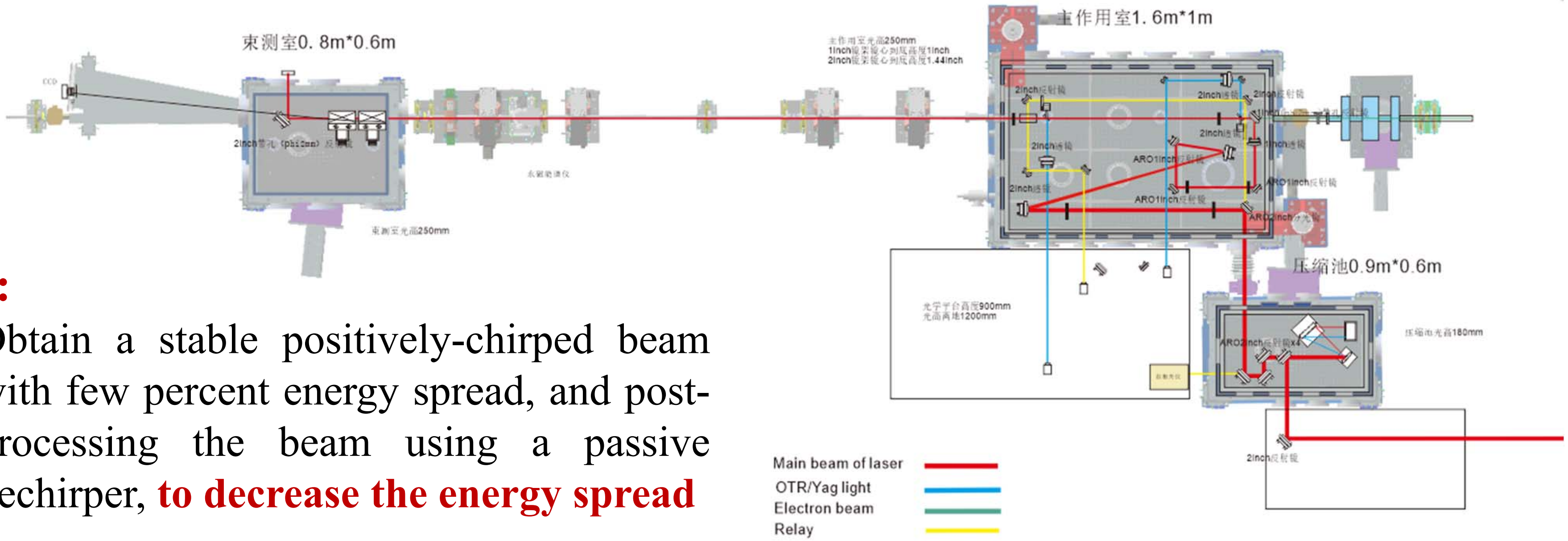
Outlines

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

Platform at SXFEL







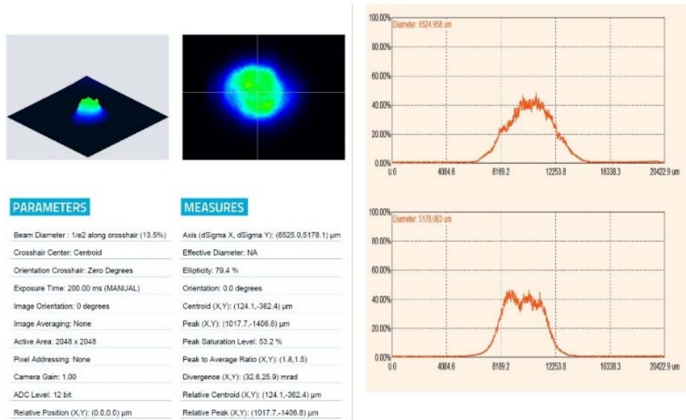
Aim:

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)

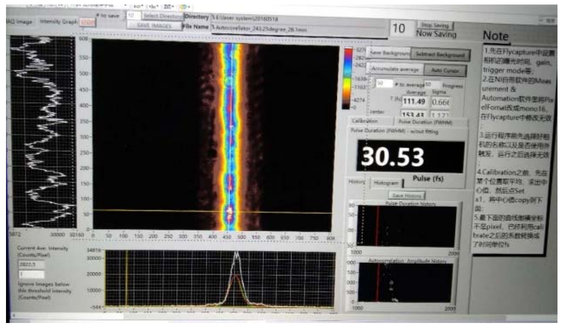
Amplifier energy performance

Amplifier output profile before expander



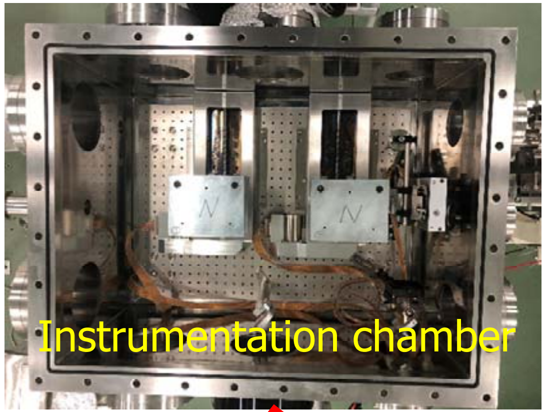
Pulse compressor efficiency: 72%

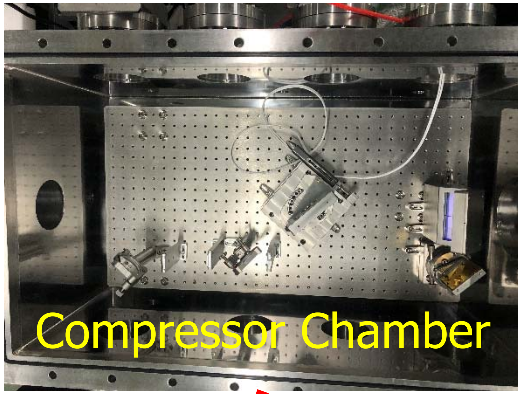
Pulse duration

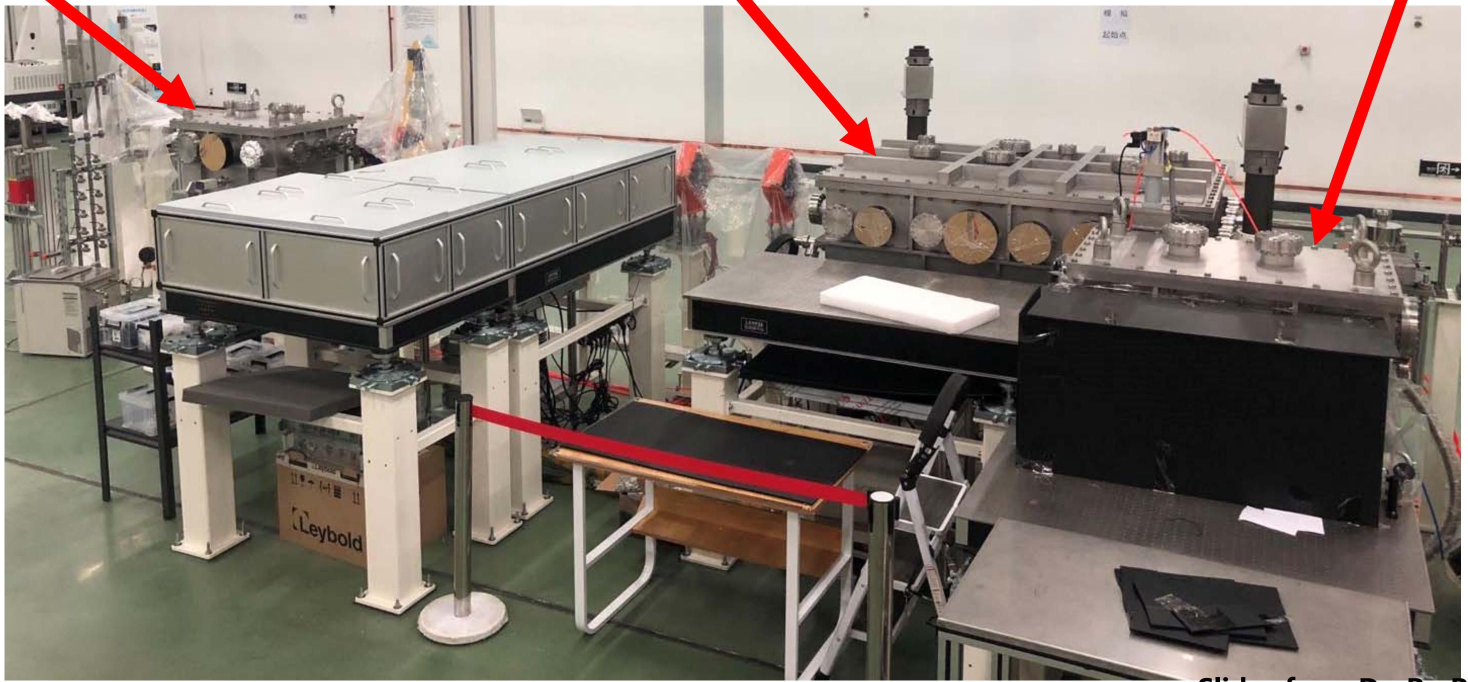


Slides from Dr. Bo Peng (2020)

Wait for the beamtime

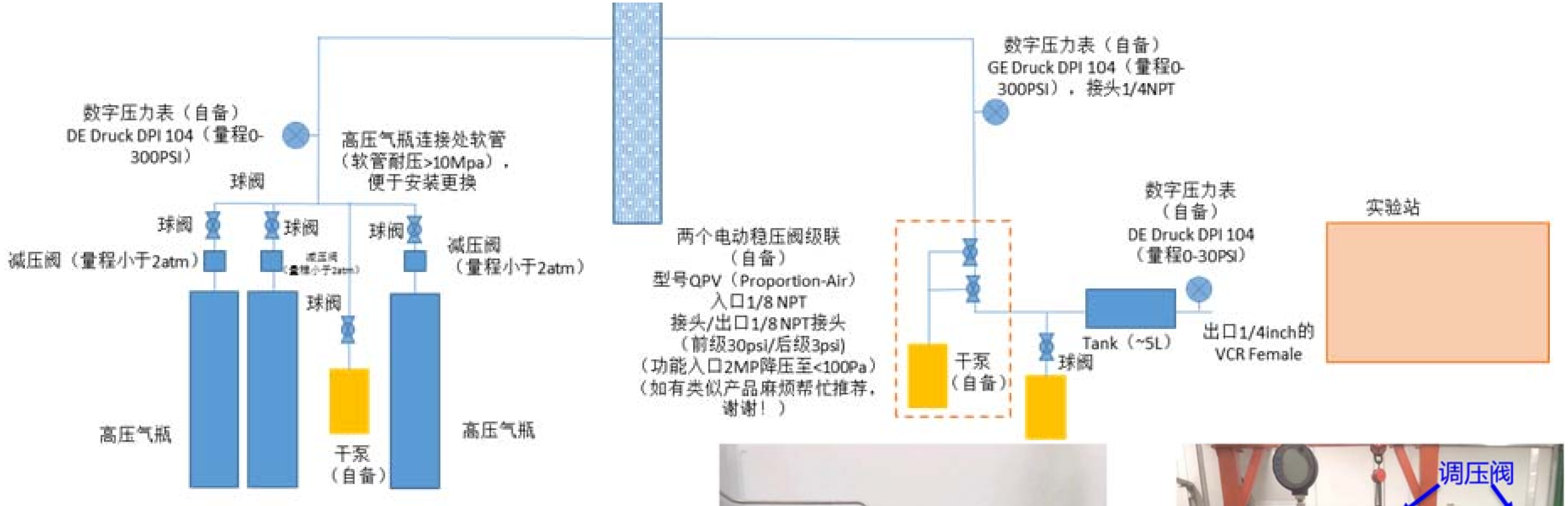






Slides from Dr. Bo Peng (2020)

Experiment preparation → gas loop

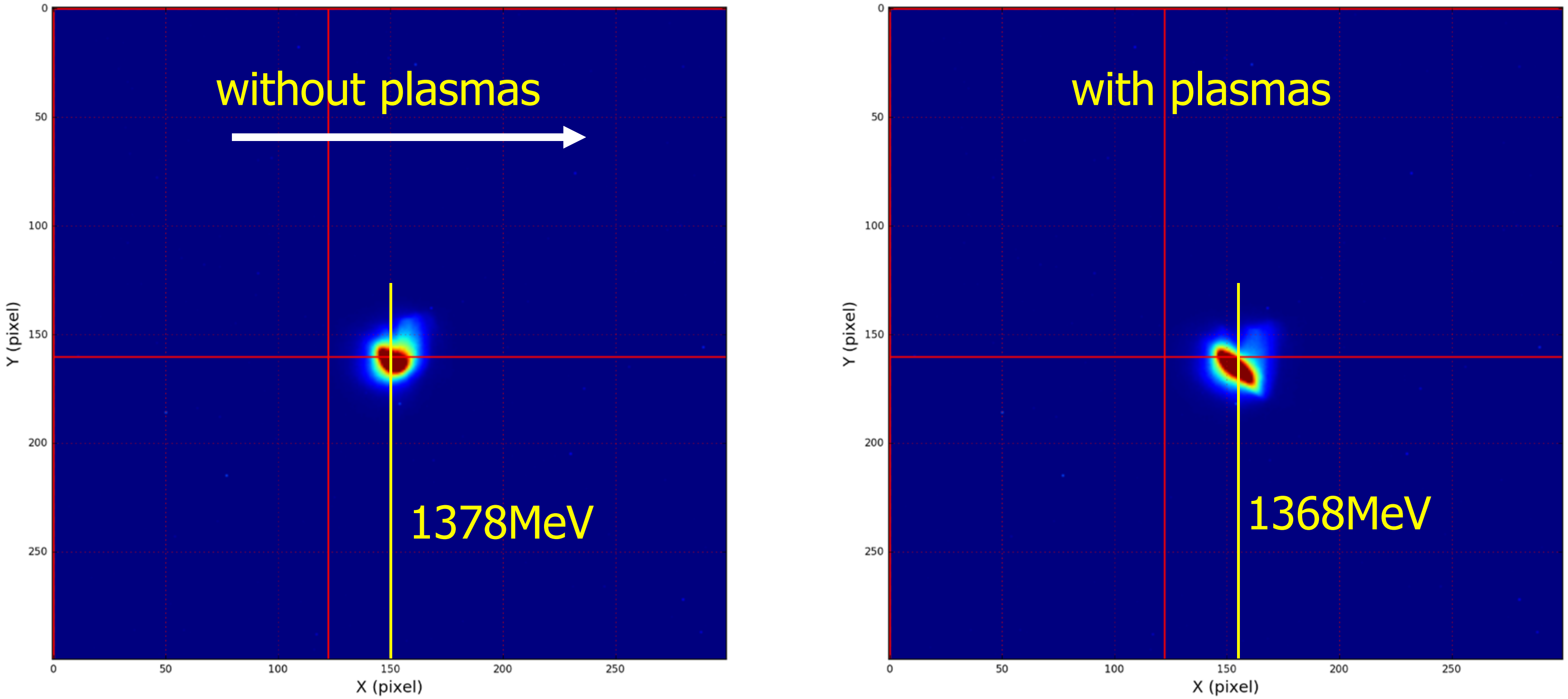


高压气瓶为混合气体（He：N2混合的摩尔比=90:10或者99:1）

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)

IARC Report on Plasma Injector -- 1

- **The transformer ratio can be reduced from 3.5 to 2.5 in current design**
  - We have done some studies on low TR scheme (the transformer ratio is 1.5, indeed) and the result seems good. More detailed error tolerance analysis is ongoing.
- **Update the simulations to use the parameters for the beams exiting C-band linac, corresponding to the new baseline for the CEPC linac**
  - The linac used for CPI is quite different from the baseline linac. For example, the bunch length and bunch size for baseline are 10 ps, 1 mm, respectively. While for the plasma injector, these numbers are 2 ps, 10 μm, respectively. However, we'll do some studies on 20 GeV Driver mode
- **CSR effects at low emittance and high peak-current should be considered**
  - The CSR effects have not been considered yet. Right now, we focused on how to maintain beam quality in the main linac. CSR effects studies will be considered in the next version design (supposed to start at the end of 2021 and be finished before June 2022) by using "Elegant" code
- **Enormous computing resources required for optimization and tolerance studies necessitates the use of models of reduced complexity**
  - Right now, we are using the open source code, QuickPIC. This is a quasi-static PIC code that can efficiently model the PWFA. For a typical problem, QuickPIC can be 1000 times faster than using a normal PIC code. The QuickPIC is continuously improved by a collaborated group. Our team member, Prof. Weiming An, is the main developer of QuickPIC

IARC Report on Plasma Injector -- 2

- **Propose and schedule appropriate experiments to test the new ideas on positron acceleration at the FACET-II facility**
  - We have submitted the e+ acceleration proposal to FACET-II committee and got a positive feedback (the remark is "good"). We hope to get beam time for our proposal in the next 2-3 years. As we showed at the beginning, one of our new positron acceleration schemes (stable asymmetric mode in hollow plasma channel) has been accepted by PRL
- **Consider how to shape the linac pulses at the photocathode gun in order to optimize the transformer ratio and avoid hosing instability**
  - Dr. Guan Shu joined our team last year, who was the key member for PITZ's e- gun design (500pC, L-band, also longitudinal shaped). He is working on our photocathode gun design. Both laser shaping and emittance exchange methods have been studied to shape the beams
- **Consider relaxing the beam-size requirements in the linac and focusing the beam at the entrance to the PWFA stage using a plasma lens**
  - We have taken the reviewers' suggestion and start simulation studies on plasma matching section. Our first goal is to relax the beam size requirement to 20 μm level, which is consistent with our original design. We also planned to carry out experimental active plasma lens studies (experiment) on THU or SJTU LWFA platform in the near future

IARC Report on Plasma Injector -- 3

- **Design and propose appropriate experiments to investigate the stability of the proposed plasma injector over many-hour and several-day periods**
  - One of the most important factors influencing the plasma injector's performance is the plasma source stability. We have already done experiments on 10-20 cm plasma tube using noble gas, produced a hollow channel plasma and used it in plasma dechirper experiments. We'll continue to fabricate a 1-meter plasma channel prototype, and test the reliability and reproducibility.
  - For the whole system stability, we need a dedicated PWFA test facility to perform appropriate experiments, which is supported by IHEP management and under serious discussion right now

- **Consider on what timescale a robust and costed proposal for a plasma injector/booster can be formulated, how it enters into an optimized cost and risk assessment and how it can be matched with the TDR/EDR timescales set out for CEPC**
  - To be honest, we don't have a detailed timetable to present a robust and costed proposal for the CEPC plasma injector right now. One important reason for this is that we still have a lot of work to do before we can assess the feasibility of the CEPC plasma injector. We planned to finish the feasibility studies by the end of 2022. A robust and costed proposal should be started at that time. Besides, the plasma injector is not a baseline scheme but an alternative scheme for CEPC. It gives us a little more time than other hardware systems and the whole CEPC TDR timetable. However, the reviewers are correct. We should consider the optimized cost and risk assessment ASAP. We'll work hard on it and hope to present some progress next year

Summary and prospects

- **Electron acceleration**
  - Start-to-end simulation is performed and preliminary results of 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. HTR 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

- **All the simulation and experimental results haven't show stopper. CPI is still at conceptual design stage, and still has a big gap to TDR or EDR stage compared with other mature systems. However, we are on an unexplored path instead of a "me too" path. Right now, keep going is more important than a clear timetable.**

Thank you!