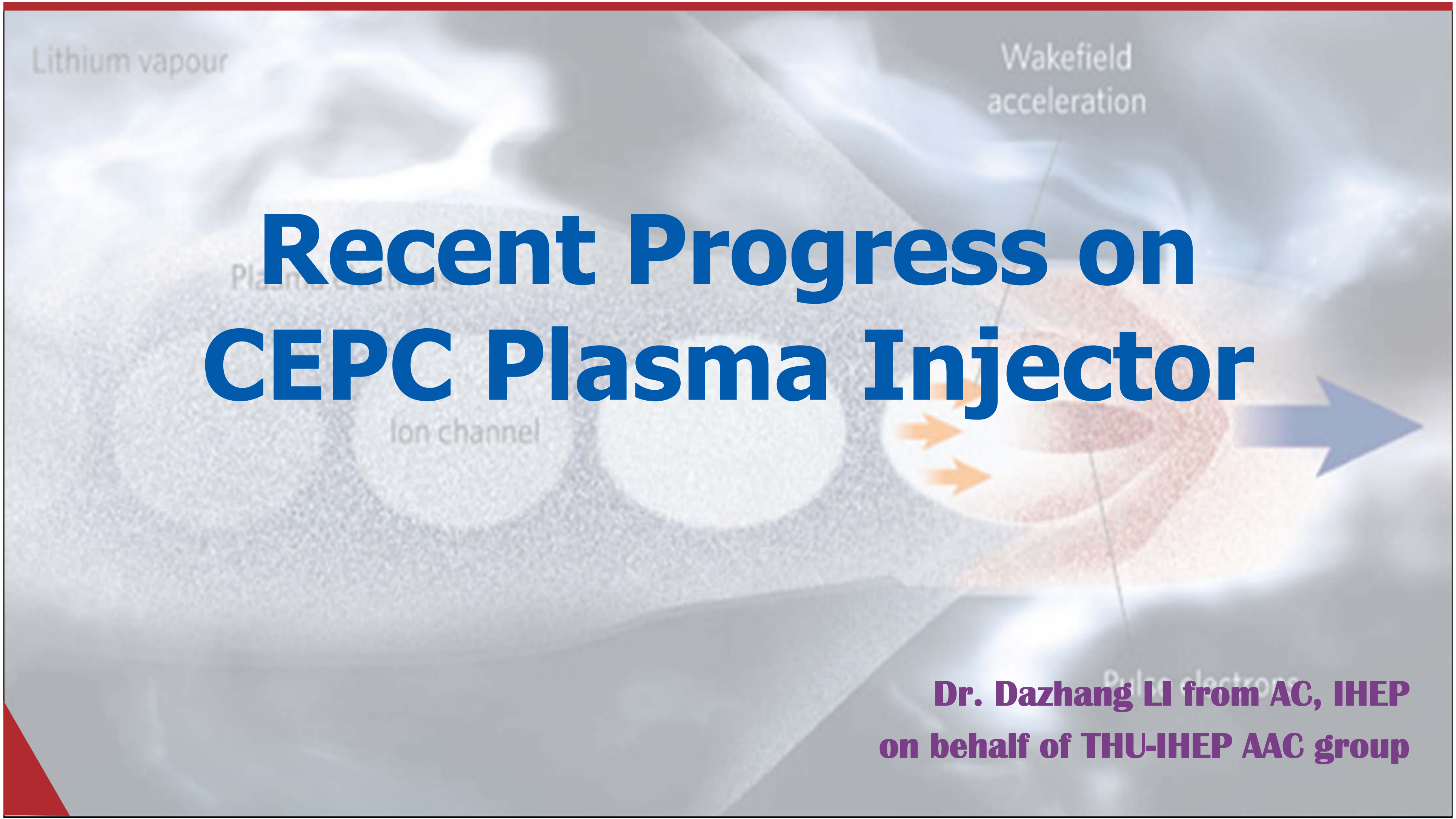
中國科學院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences



Recent Progress on CEPC Plasma Injector

Dr. Dazhang LI from AC, IHEP
on behalf of THU-IHEP AAC group

Outlines

- PWFA error analysis and hosing instability
    - ✓ Flashback: tolerance studies last year
    - ✓ Shorter drive beam and lower transformer ratio
    - ✓ General analysis on hosing instability
- "Perfect" beam loading for a two-bunch PWFA
- Preliminary results on PWFA experiment @ SXFEL
- PWFA test facility consideration

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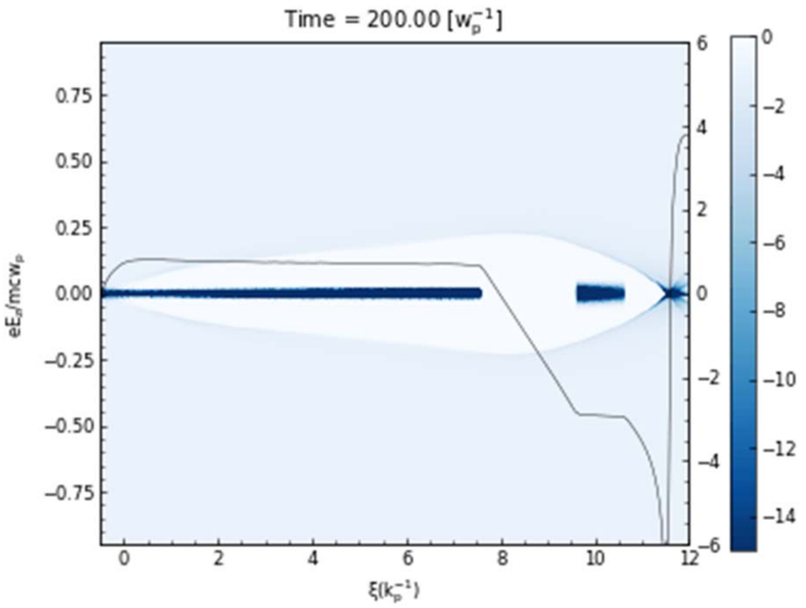
HTR e- acceleration without error



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
Energy spread $\delta_E(\%)$	0.56
TR	~ 4
Efficiency (%) (driver → trailer)	59.1

- **10 GeV → 45.5 GeV e- acceleration, R~4**
- **ne = 5×10^{15} cm^{-3}, the driver is about 2 ps (600 μm, $\xi \sim 8$)**
- **Hosing instability occurs at ~ 130000 ω_p^{-1} and start to lose particles at ~ 150000 ω_p^{-1}**
- **Assuming fully symmetric drive and witness bunches !**

Error analysis → fully symmetry

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
beam distance		[-1um, 0.25um]	E_t
initial energy spread		3.9%	E_t δ_E
Spot size	driver	[-40%, 2%]	E_t
	trailer	[8%, 8%]	E_t

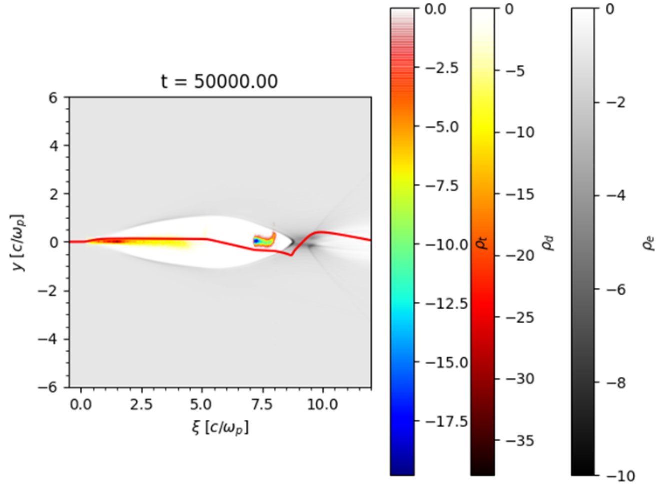
Error analysis → not fully symmetry

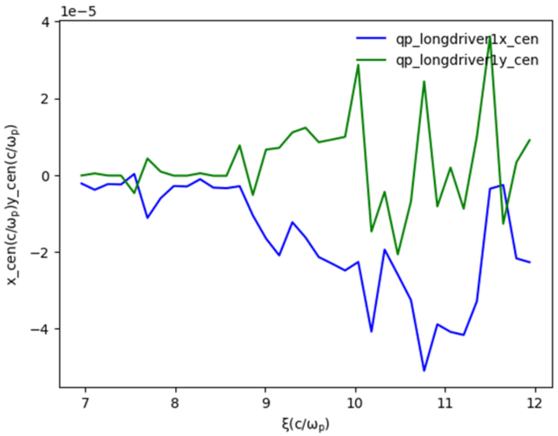
Slice jitter	Transverse position	Driver	±0.025nm
		Trailer	±3.7um
	Transverse velocity	Driver	<0.1nrad
		Trailer	<5urad

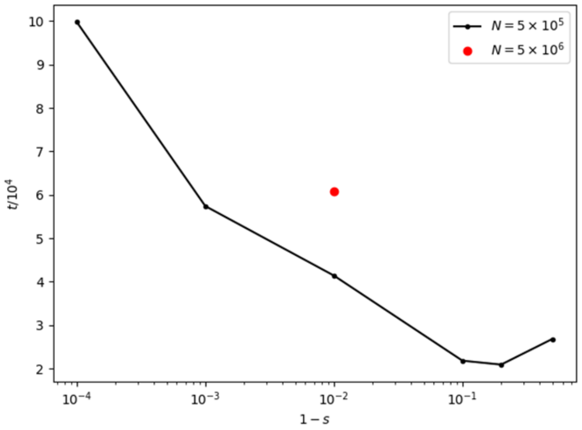
metry, even let $<x_d> = 0$, the example, adding only 0.025nm Actually, the resolution of the d noise. Is it physical or not?

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}

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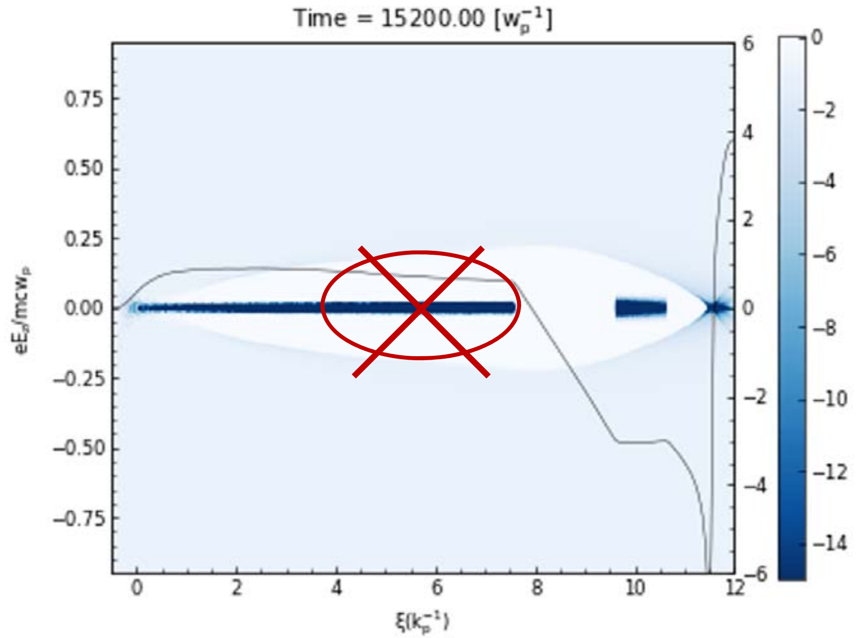
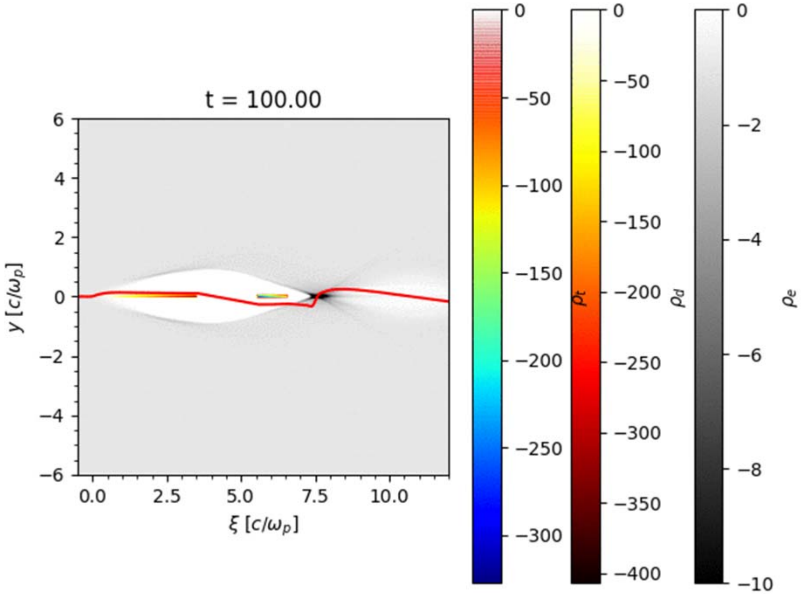
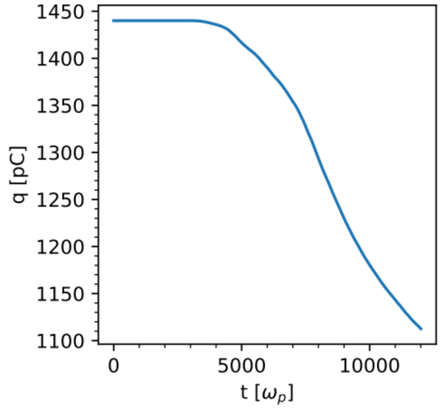
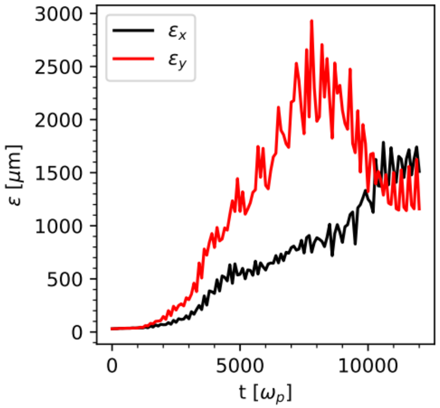
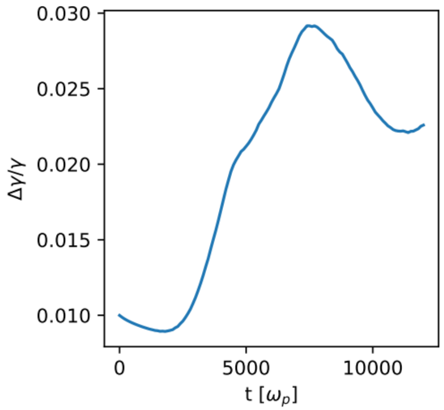
Short driver for more stable acc.

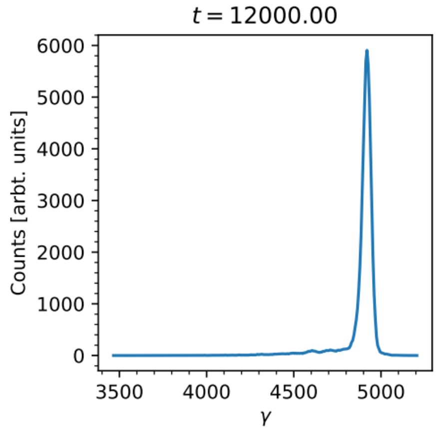












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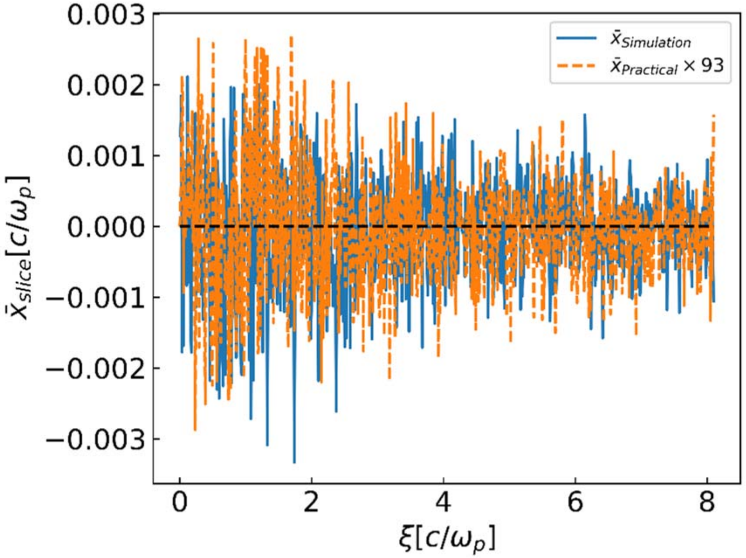
Initial noise macro vs. practicacl

- 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 $N\left(0,\ \sigma_r/\sqrt{N}\right)$
- For PIC simulation, number of macro particle is much less than practical particle number, so the initial noise level is different in magnitudes.
- 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

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

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

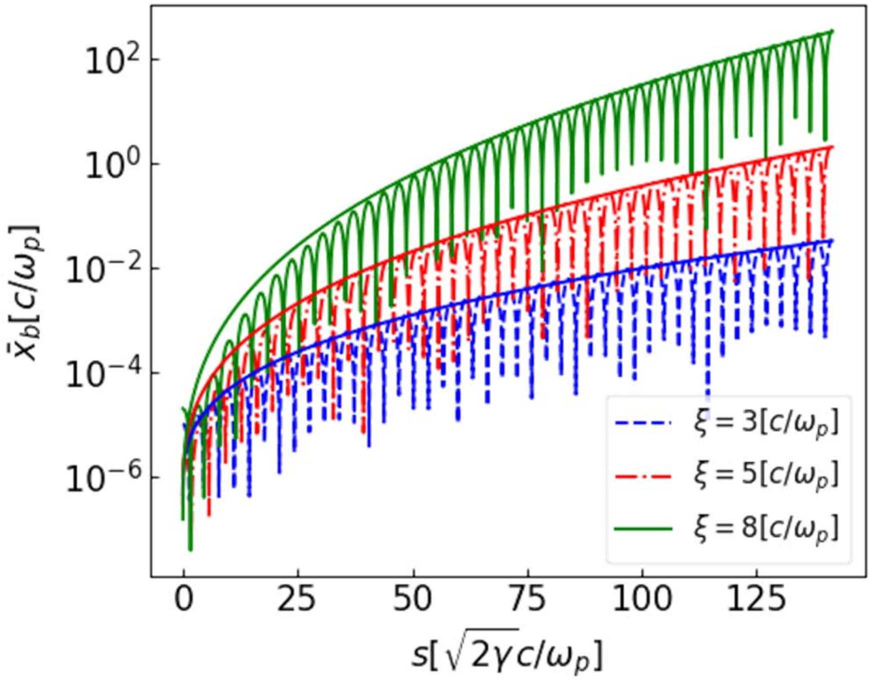
  - Under this limit, $\partial_s \ll k_\beta, \partial_\xi \gg \omega_0$, and we have

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

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

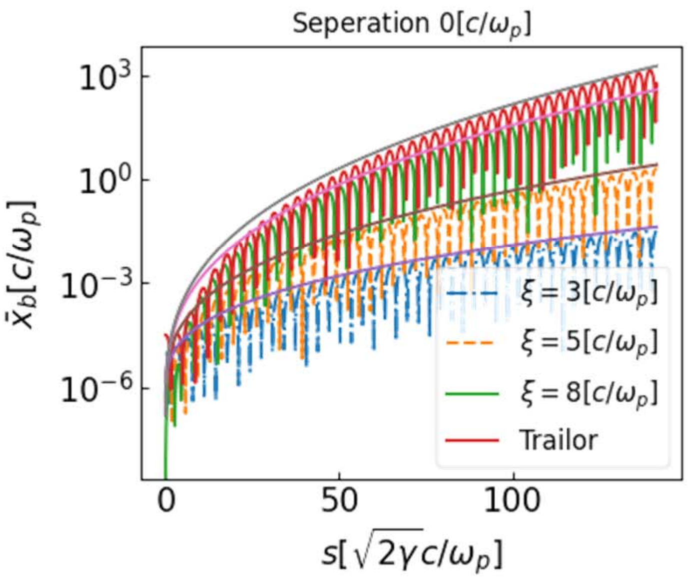
  - Let $\bar{x} = Ae^{\gamma_0 (k_\beta s)^m (\omega_0 \xi)^n}$

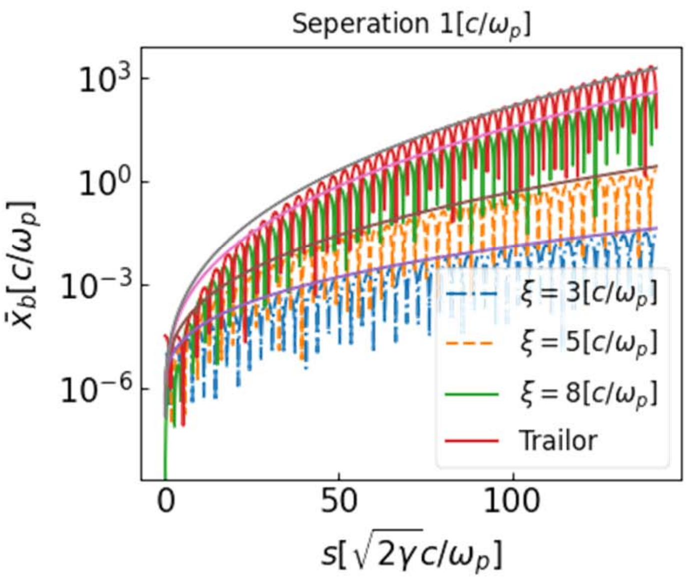
$$\partial_\xi^2 \partial_s \bar{x}_b = \frac{\omega_0^2 k_\beta^2}{2ik_\beta} \bar{x}_b$$



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

Witness beam’s hosing instability





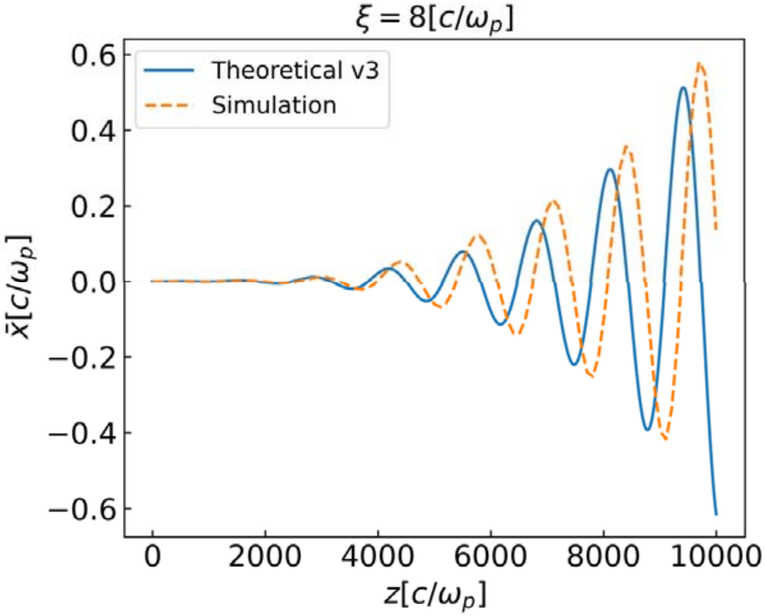
Different separation has little effects on hosing growth. Which means bunch train may not effective for damping hosing instability

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

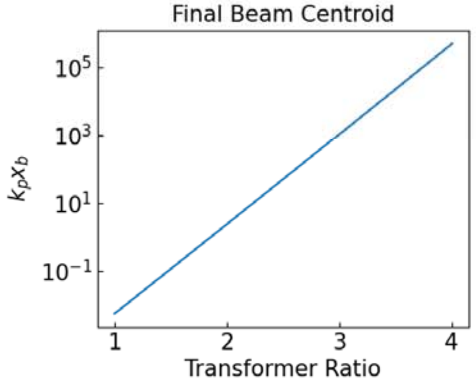
Transformer Ratio limitation

- 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 $k_p s \sim \gamma_0 R$

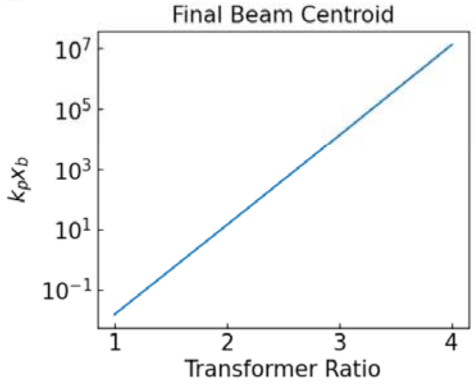
➢ We can obtain the final beam centroid of the witness beam at the end of the acceleration

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

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

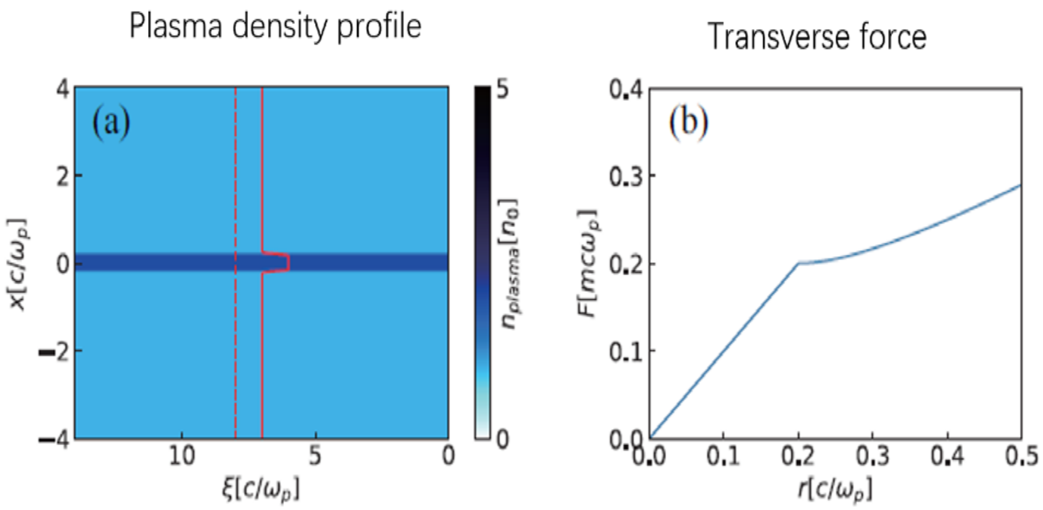


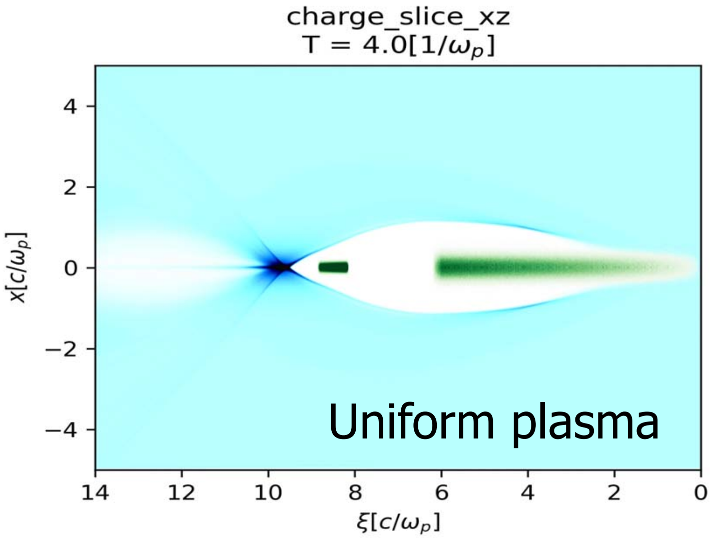
➢ For a 20GeV driver, beam size $k_p\sigma_r = 0.2$, c=0.7, $c_b = 0.8$



Transformer ratio 1-1.5 is acceptable without extra damping regime

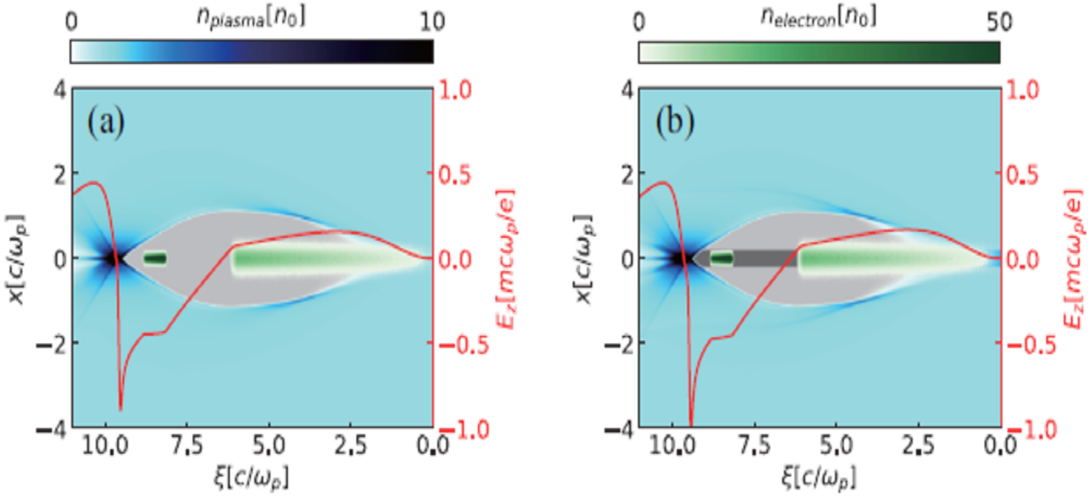
One powerful damping method

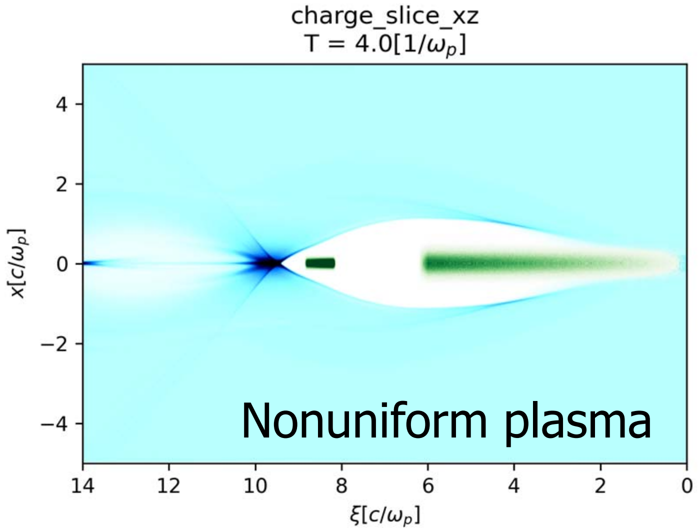




Uniform plasma

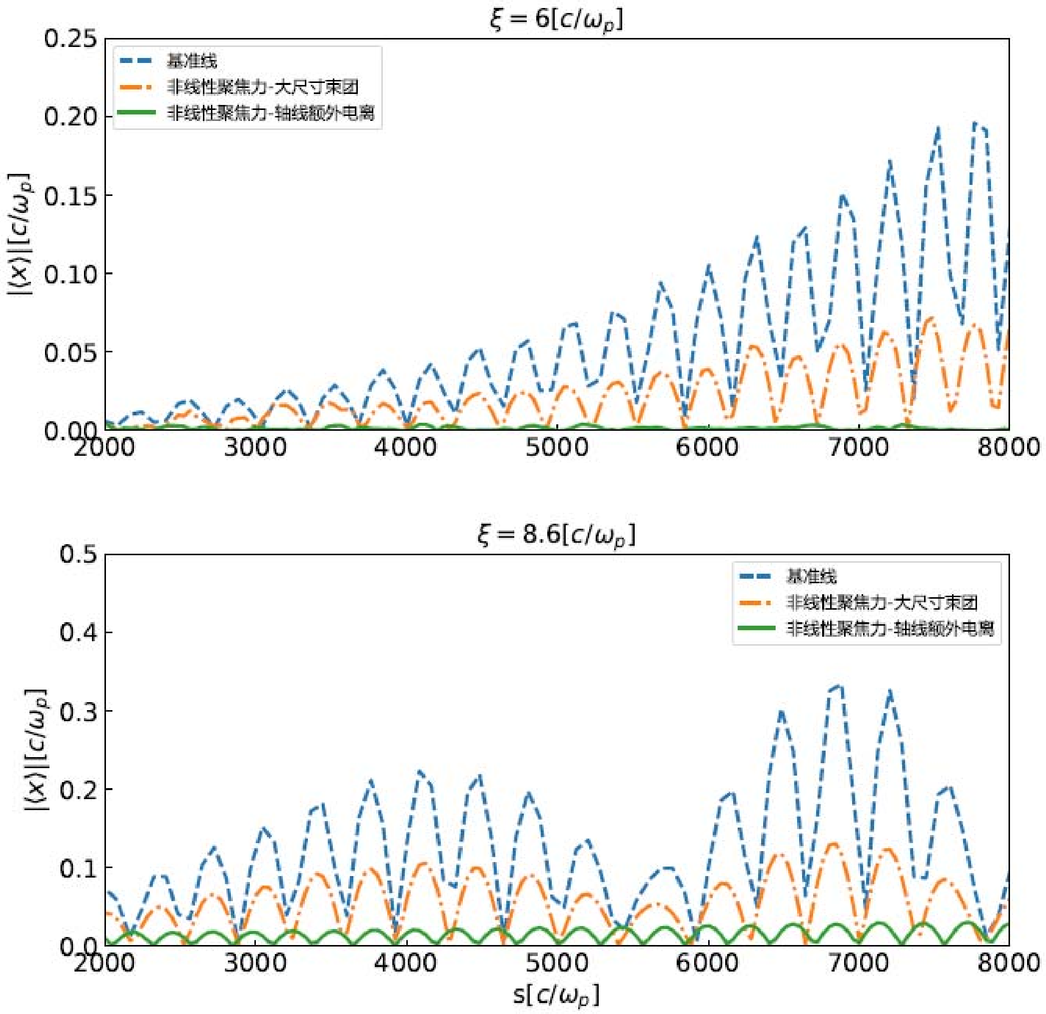
Little effects on Ez field





Nonuniform plasma

One powerful damping method



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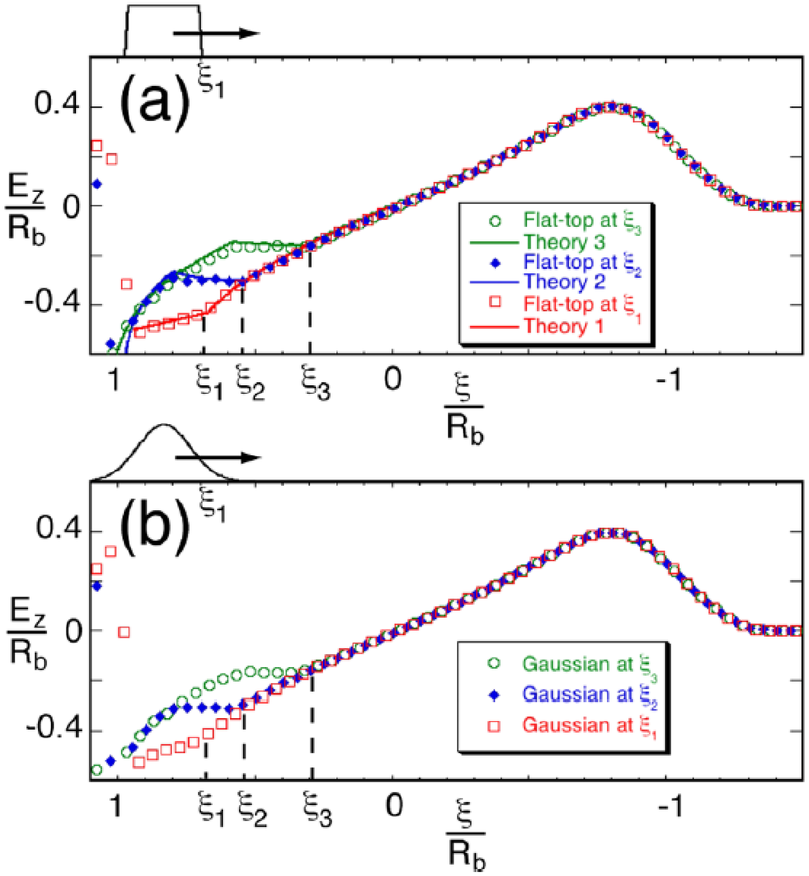
Motivation: find a matched condition



M. Tzoufras,W. Lu, et al.,Phys Rev Lett101, 145002 (2008)

$$Q_s E_s = \frac{\pi R_b^4}{16}$$

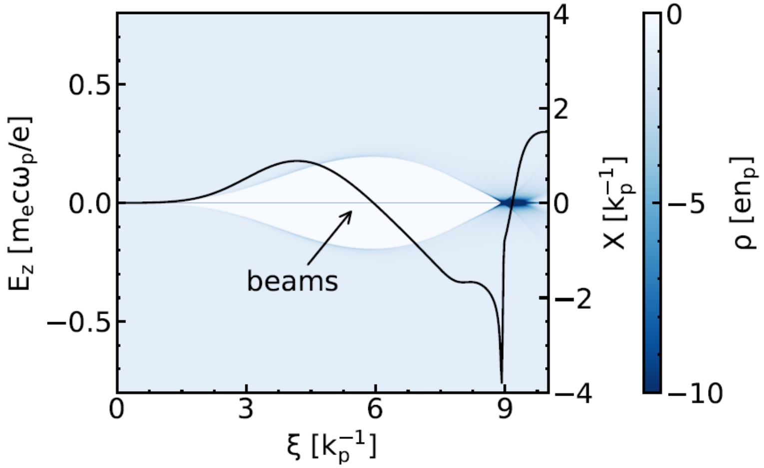
R_b: the maximum radius of the ion channel

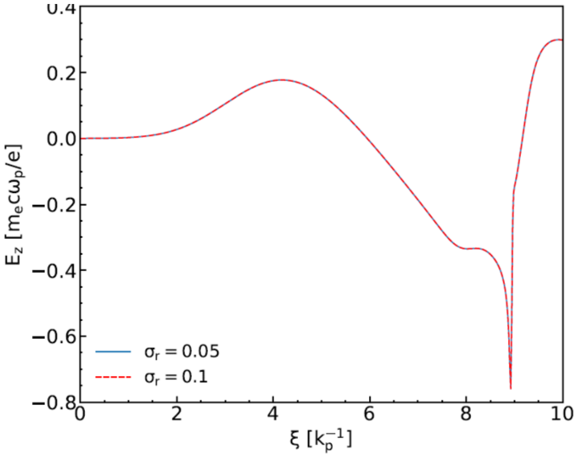
Q_s: the total charge of trailer

E_s: the longitudinal wakefield at ξ_s

- Not related to driver parameters
- Based on the assumption R_b >>1
- Our goal: find proper bunch parameters of $(Q_d, Q_t, \sigma_{zd}, \sigma_{zt}, \sigma_{rd}, \sigma_{rt}, d_{dt}, n_p)$

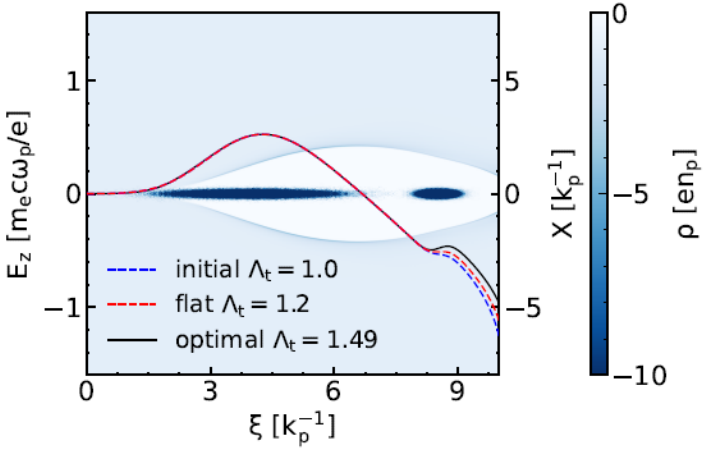
Ignore σ_r when $\sigma_r << R_b$





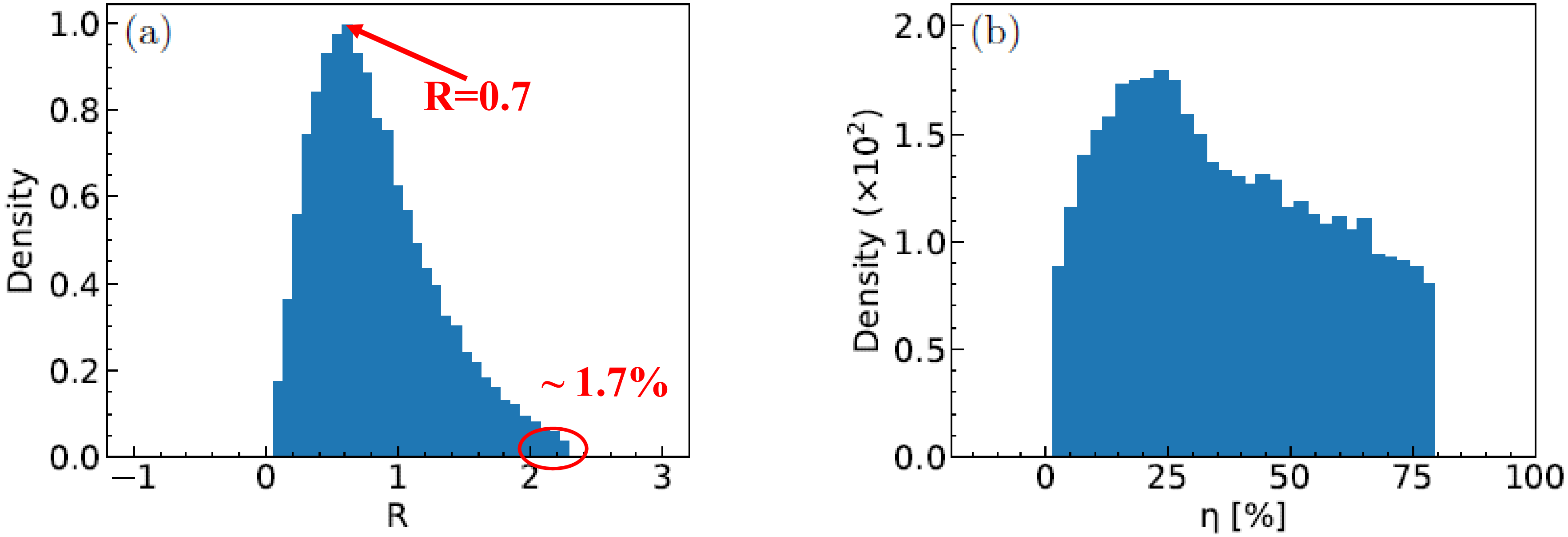
The acceleration structure is determined by the normalized charge per unit length $\Lambda = n_b \sigma_r^2$ (not related to σ_r)

For given $\Lambda_d, \sigma_{zd}, \sigma_{zt}, d_{dt}$, we introduce BFGS (one of the most effective algorithms of quasi-Newton group) to find optimal Λ_t for smallest energy spread. Then we can get transformer ratio R directly in such condition.



- δ_E = 1.69% at optimal Λ_t=1.49
- δ_E = 2.35% at Λ_t=1.2
- Optimization time: 7min

Statistics of the optimization



- Optimization average time: 7.6min

- Scanned a wide range bunch parameters (referenced FACET-II, FLASHForward, CLIC…)

  Λ_d: [0.0885,7.70] σ_{zd}: [0.0952,1.90] Λ_t: [0.0627,3.14] σ_{zt}: [0.0952,0.857]

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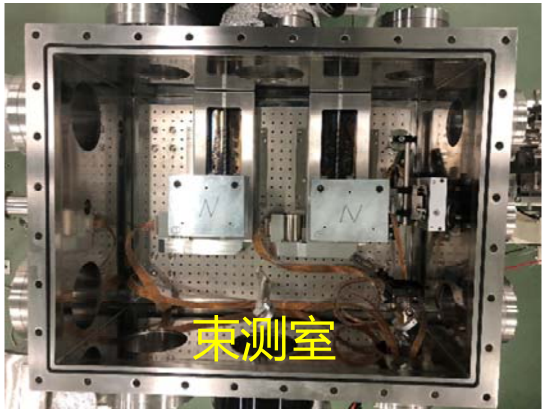
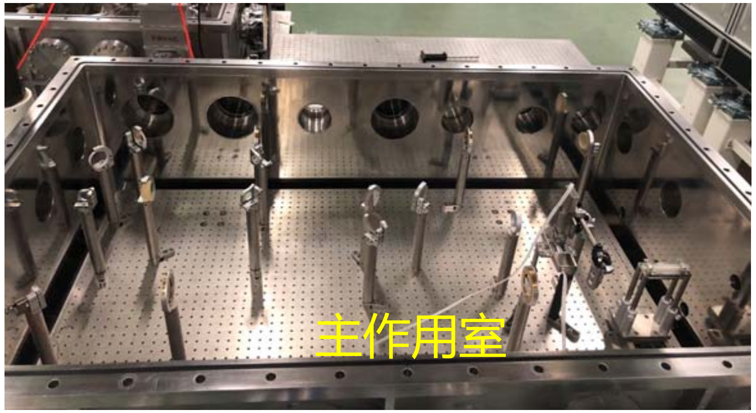
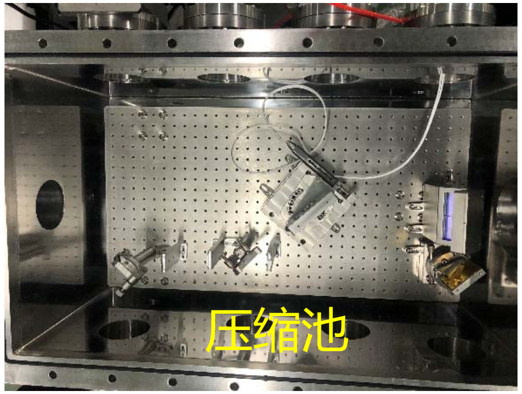
Experiment preparation @ SXFEL

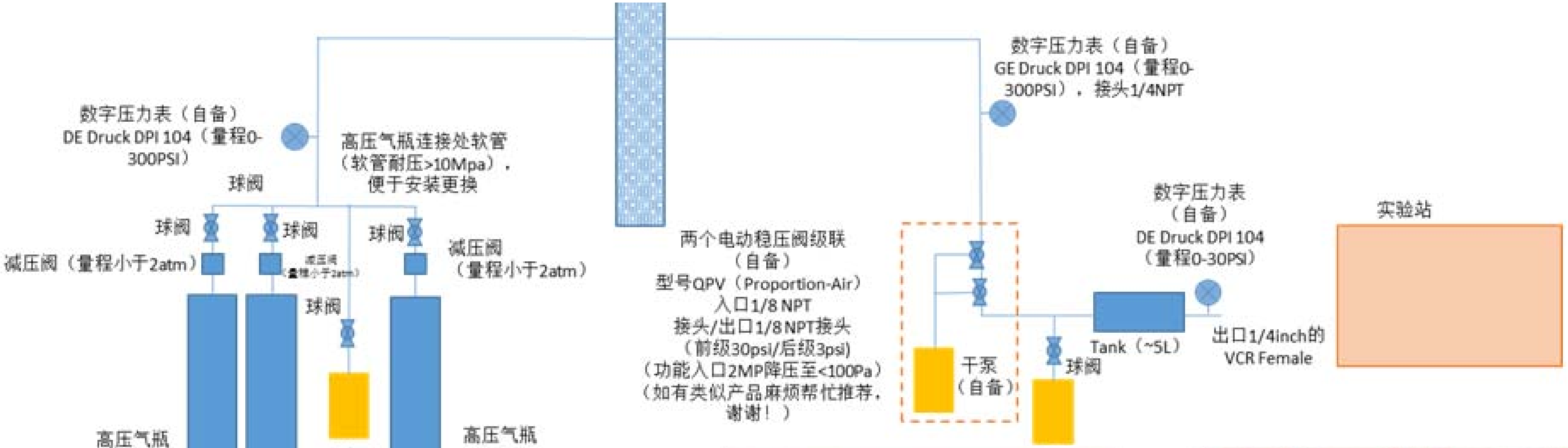






Slides from Dr. Bo Peng (2020)

Experiment preparation → gas loop



数字压力表（自备）
DE Druck DPI 104（量程0-300PSI）

球阀

高压气瓶连接处软管
（软管耐压>10Mpa），
便于安装更换

球阀

球阀

球阀

减压阀（量程小于2atm）

减压阀（量程小于2atm）

减压阀
（量程小于2atm）

球阀

高压气瓶

干泵
（自备）

高压气瓶

数字压力表（自备）
GE Druck DPI 104（量程0-300PSI），接头1/4NPT

两个电动稳压阀级联
（自备）
型号QPV（Proportion-Air）
入口1/8 NPT
接头/出口1/8 NPT接头
（前级30psi/后级3psi)
（功能入口2MP降压至<100Pa）
（如有类似产品麻烦帮忙推荐，
谢谢！）

干泵
（自备）

球阀

Tank（~5L）

数字压力表
（自备）
DE Druck DPI 104
（量程0-30PSI）

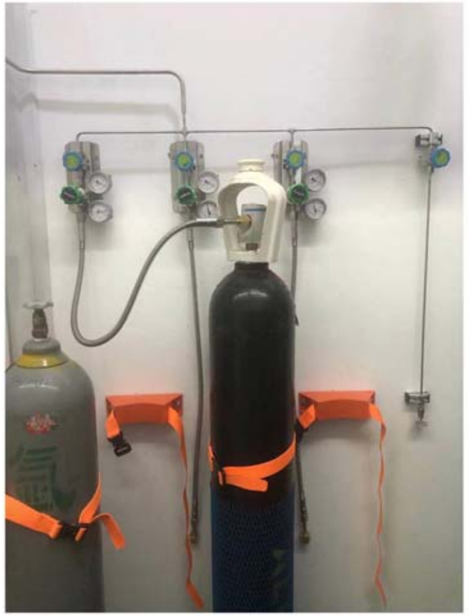
出口1/4inch的
VCR Female

实验站

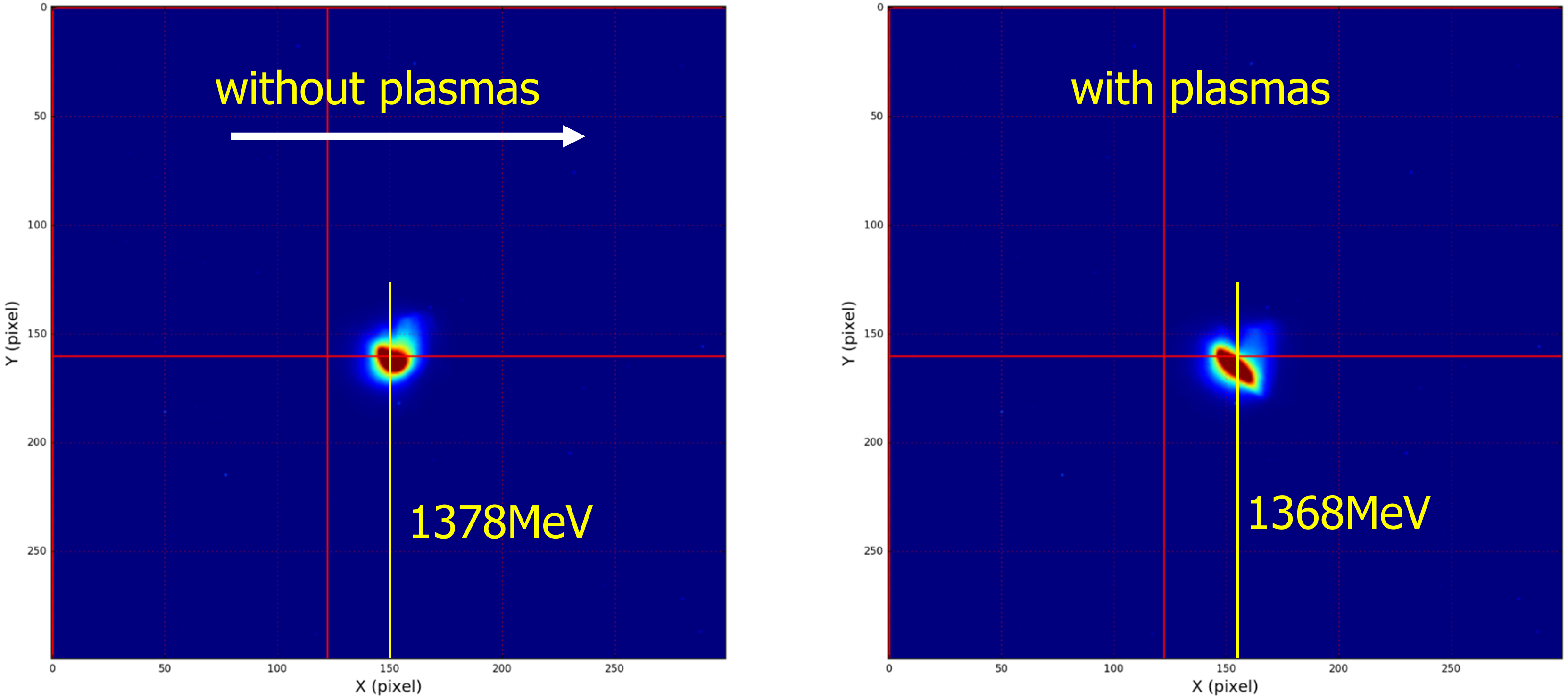
高压气瓶为混合气体（He：N2混合的摩尔比=90:10或者99:1）

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)

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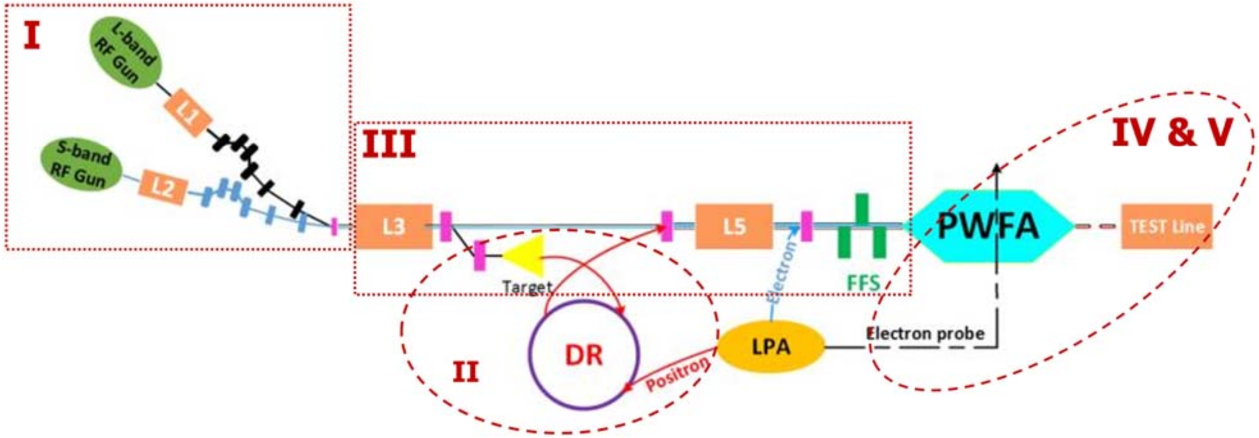
Test facility for plasma-based acc.



Key requirements of the test facility:

- High charge L-band e- gun → > 6 nC / bunch
- Longitudinal shaped bunch → laser shaping and/or EE
- Longitudinal modulation at transport line
- Two e- bunches "perfect" merging → Essentially solved, with ~ 1% energy difference
- e- Bunch compressor design → optimized (2 bunches compressed in one structure)
- FFS to achieve very small beam size → ~ 40μm @ 1 GeV/ 30 mm·mrad
- Cascaded with plasma accelerator → need plasma matching section
- High current, low emittance e+ beam → low energy damping/stacking ring under consideration
- Very precise beam instrumentation and control → better than 10 fs / 1μm

Summary and prospects

- **Hosing instability and error analysis**
  - The asymptotic solution of hosing equations agrees well with the numerical solution, and the numerical solution can agree well with the PIC simulation results.
  - Without extra damping mechanism, the growth of hosing instability from statistical noise is acceptable when transformer ratio is 1-1.5
  - There are other powerful damping mechanisms. HTR is still possible
- **Experiment at SXFEL**
  - Finally the experiment started. So far the beam time is still limited
  - A dedicated test facility is absolutely necessary
- **PWFA Test facility consideration**
  - Try to optimized linac design to meet the requirement of low beam energy and high charge
  - Positron beamline and damping ring are under design
  - For worst condition, high efficiency and reasonable linac requirement could be ensured, with the transformer ration around 1.5

Thanks!