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

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

Outlines

- Introduction
- Recent progress on CEPC plasma injector
  - Linac requirement of CPI
  - High transformer ratio e- acceleration
  - Investigation positron acceleration
  - Performed & proposed experiments
- Summary and prospects

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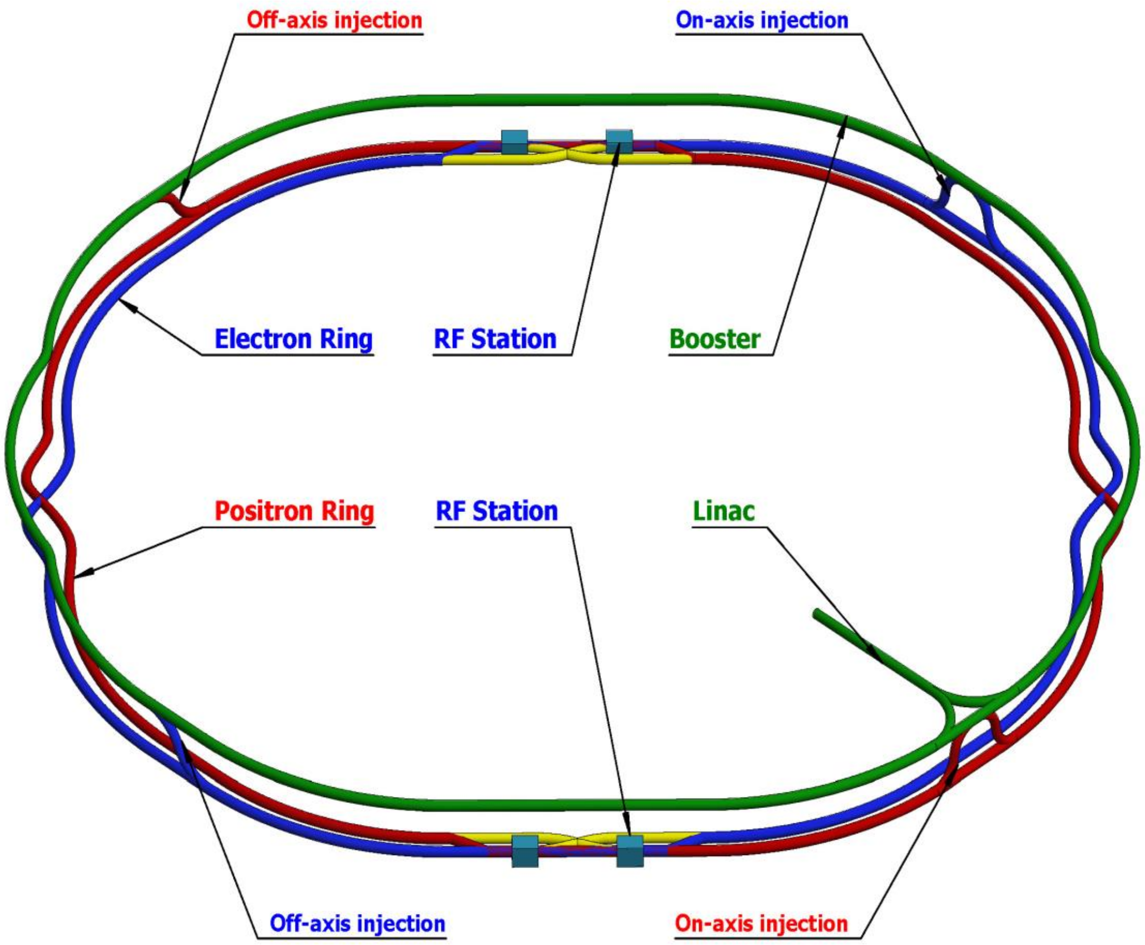
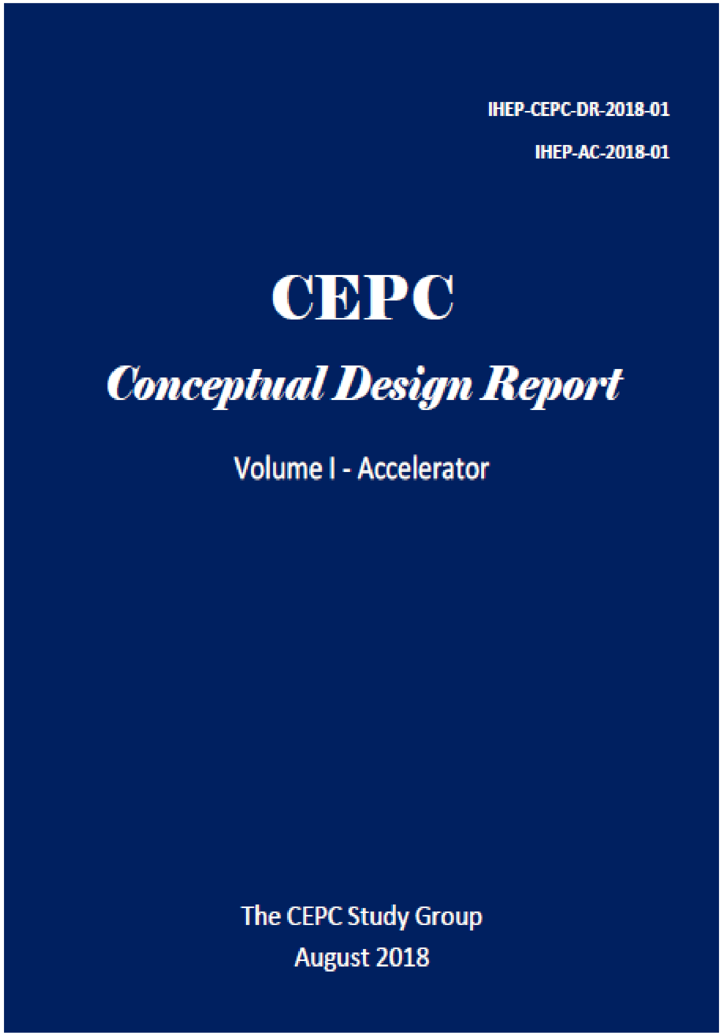
Circular Electron Positron Collider





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

CEPC Low field Dipole in Booster Ring

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

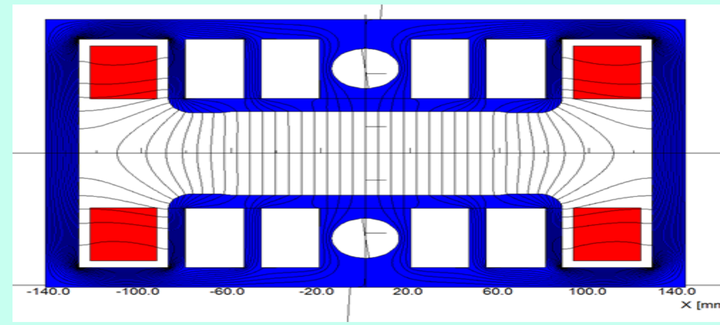
- Field error <29Gs*0.1%=0.029Gs → how to design
- Field reproducibility <29Gs*0.05%=0.015Gs → how to measure
- The Earth field ~0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

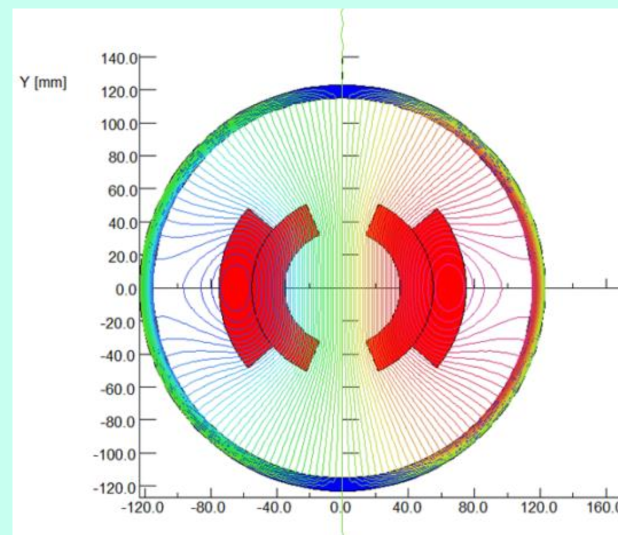
➢ Thinking beyond CDR

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

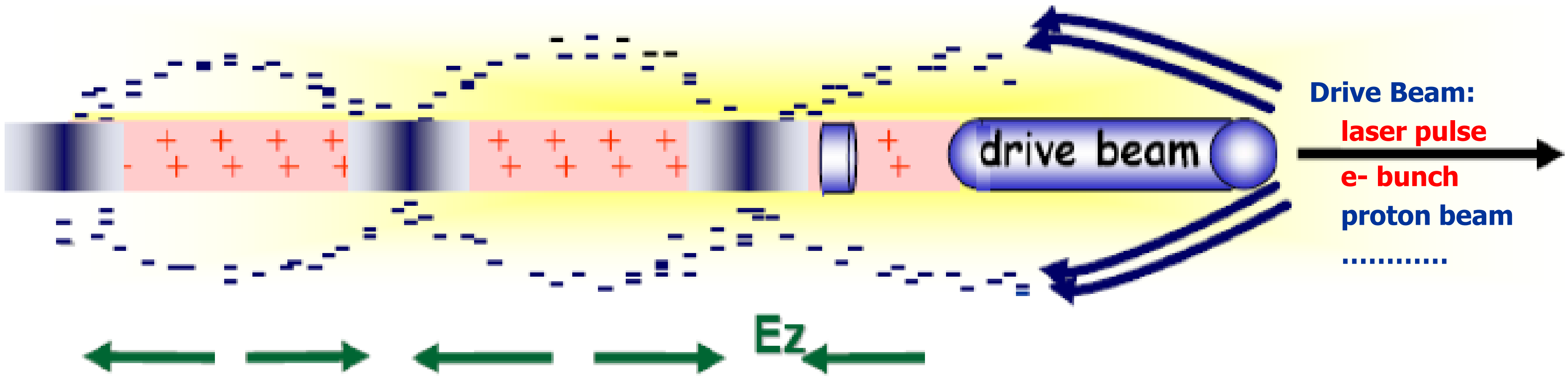
- Sextupole coils outside vacuum chamber

Without magnetic core
(Twice excitation current)





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)

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

Plasma wave excitation, 1~100GeV/m gradient

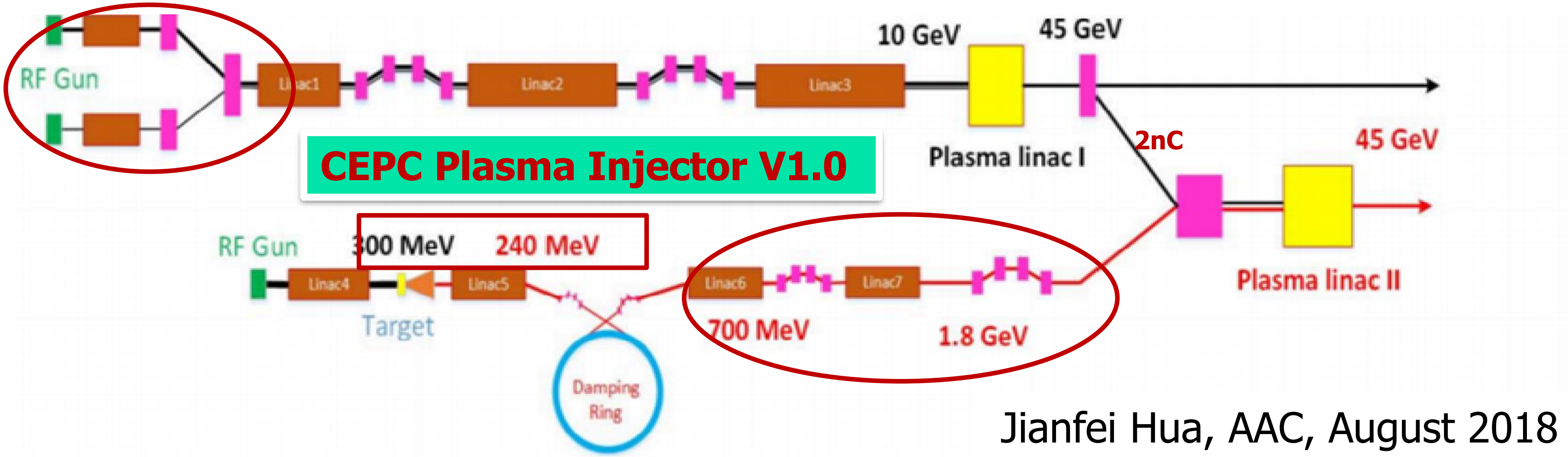
Footprints of CPI

- **2017.01: First discussion on CPI**
- **2017.03: 1st THU-IHEP AAC group meeting**
- **2018.08: CPI conceptual design V1.0**
- **2018.11: CEPC CDR released, CPI mentioned as a backup injection method**
- **2019.09: CPI conceptual design V2.0**
- **2020.09: Linac requirement updated from CPI**

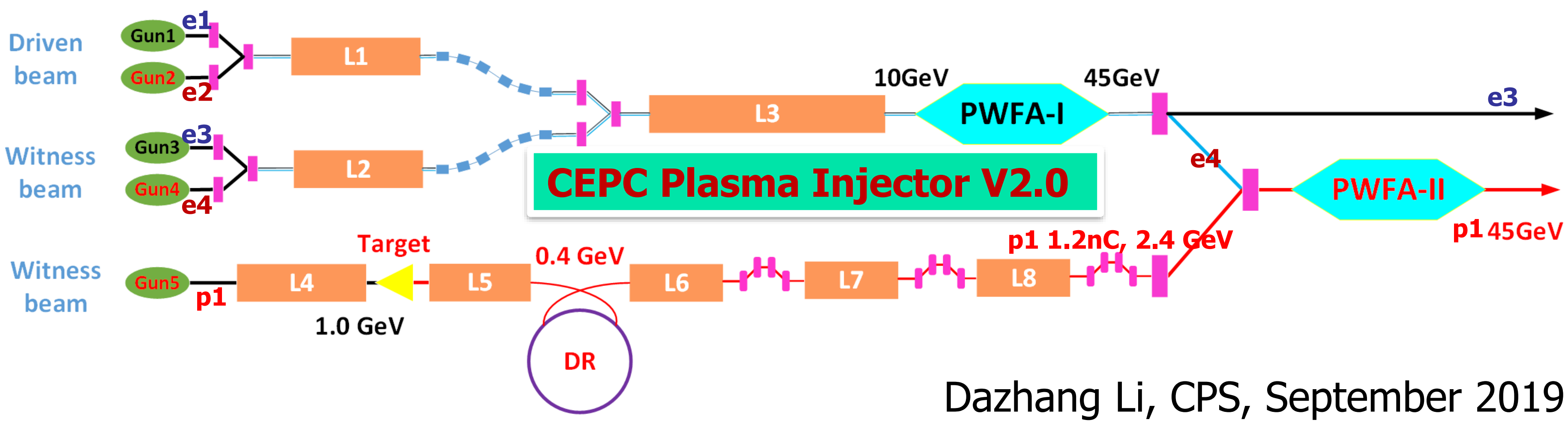
A young and fast growing group

- **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……
- **THU 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

CPI conceptual Design V1.0→V2.0



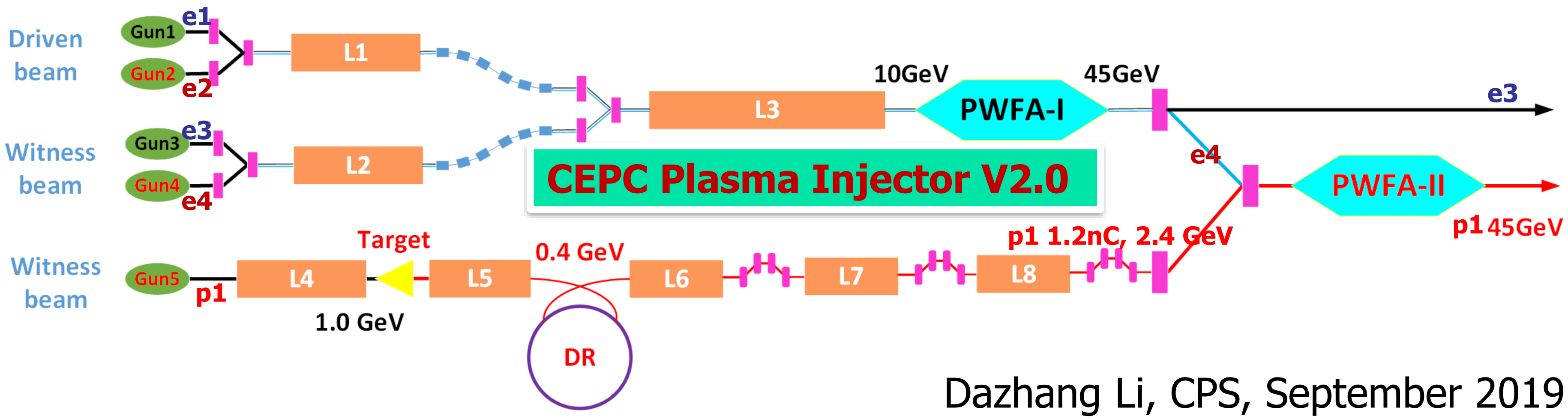
Jianfei Hua, AAC, August 2018



Dazhang Li, CPS, September 2019

Key issues of CPI

- **Electron Acceleration**
  - High transformer Ratio, High efficiency, Stability and error analysis
- **Positron Acceleration**
  - Stable acceleration (different schemes), energy spread control, efficiency enhancement, Stability and error analysis……
- **Conventional Accelerator design and optimization**
  - Photon-guns, Linac, Positron generation and damping ring ……
- **Beam manipulations:**
  - Dechirper, external injection, staging and cascading ……



Dazhang Li, CPS, September 2019

CEPC plasma injector timeline

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Requirement from Booster to CPI

Table 5.1.1: Main parameters for the booster at injection energy

		H	W	Z
Beam energy	GeV	10		
Bunch number		242	1524	6000
Threshold of single bunch current	μA	25.7		
Threshold of beam current (limited by coupled bunch instability)	mA	100		
Bunch charge	nC	0.78	0.63	0.45
Single bunch current	μA	2.3	1.8	1.3
Beam current	mA	0.57	2.86	7.51
Energy spread	%	0.0078		
Synchrotron radiation loss/turn	keV	73.5		
Momentum compaction factor	10^{-5}	2.44		
Emittance	nm	0.025		
Natural chromaticity	H/V	-336/-333		
RF voltage	MV	62.7		
Betatron tune $\nu_x/\nu_y/\nu_s$		263.2/261.2/0.1		
RF energy acceptance	%	1.9		
Damping time	s	90.7		
Bunch length of linac beam	mm	1.0		
Energy spread of linac beam	%	0.16		
Emittance of linac beam	nm	40~120		

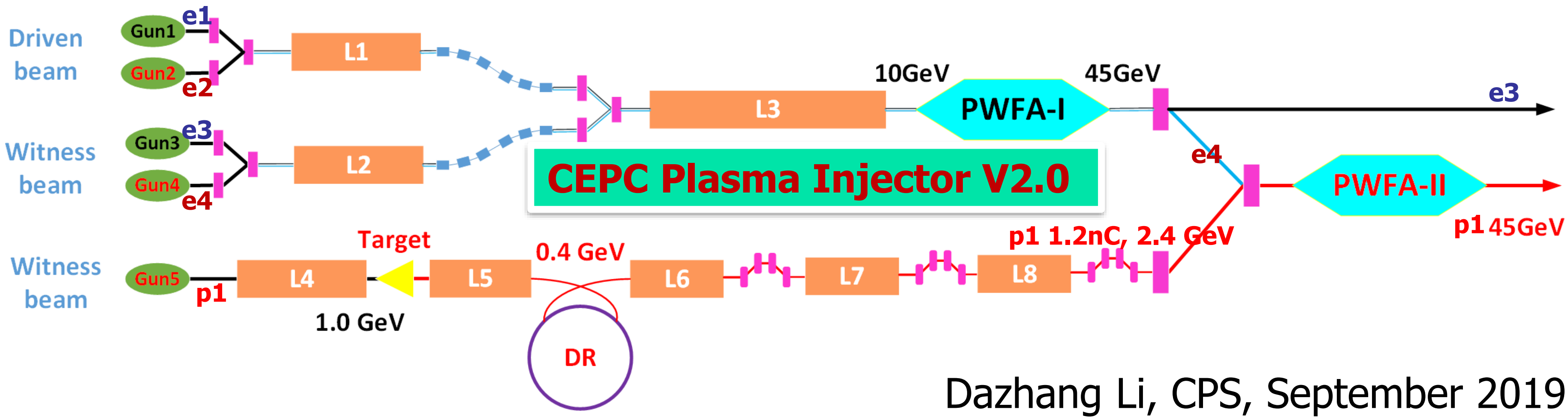
Booster Requirement	
Energy (GeV)	45.5
Bunch Charge (nC)	0.78
Bunch length(um)	<3000
Energy Spread(%)	0.2
ε_N(μm·rad)	<800
Bunch Size(um)	<2000

Table 5.1.2: Main parameters for the booster at extraction energy

		H		W	Z
		Off axis injection	On axis injection	Off axis injection	Off axis injection
Beam energy	GeV	120		80	45.5
Bunch number		242	235+7	1524	6000
Maximum bunch charge	nC	0.72	24.0	0.58	0.41
Maximum single bunch current	μA	2.1	70	1.7	1.2
Threshold of single bunch current	μA	300			
Threshold of beam current (limited by RF power)	mA	1.0		4.0	10.0
Beam current	mA	0.52	1.0	2.63	6.91
Injection duration for top-up (Both beams)	s	25.8	35.4	45.8	275.2
Injection interval for top-up	s	47.0		153.0	504.0
Current decay during injection interval		3%			
Energy spread	%	0.094		0.062	0.036
Synchrotron radiation loss/turn	GeV	1.52		0.3	0.032
Momentum compaction factor	10^{-5}	2.44			
Emittance	nm	3.57		1.59	0.51
Natural chromaticity	H/V	-336/-333			
Betatron tune ν_x/ν_y		263.2/261.2			
RF voltage	GV	1.97		0.585	0.287
Longitudinal tune		0.13		0.10	0.10
RF energy acceptance	%	1.0		1.2	1.8
Damping time	ms	52		177	963
Natural bunch length	mm	2.8		2.4	1.3
Injection duration from empty ring	h	0.17		0.25	2.2

CEPC CDR (2018)

Linac Requirement based on V2.0



Dazhang Li, CPS, September 2019

	e1/e3 Before PWFA-I	e2/e4 Before PWFA-I	p1 Before PWFA-II	e3 After PWFA-I	e4 After PWFA-I	p1 After PWFA-II	Booster Requirement
Energy (GeV)	10/10	10/10	2.4	45.5	45.5	45.5	45.5
Bunch Charge (nC)	[illegible]	[illegible]	[illegible]	1	>3	1	0.78
Bunch length (ps)	[illegible]	[illegible]	[illegible]	<1*	<1	<1*	<10
Energy Spread	[illegible]	[illegible]	[illegible]	~1%	1%	~1%	0.2%
E_{normal} (μm·rad)	<50/<100	<50/<100	<50	~100	~100	~100	<800
Bunch Size (μm)	20/20	30/20	20	<20	<20	<20	<2000

ALMOST FIXED
NEED OPTIMIZE
BASIS OF PA/EA

MAY CHANGE A LOT
NO MUCH STUDY

NOT CHANGE A LOT
SPENT SOME TIME

* Need add a plasma dechirper

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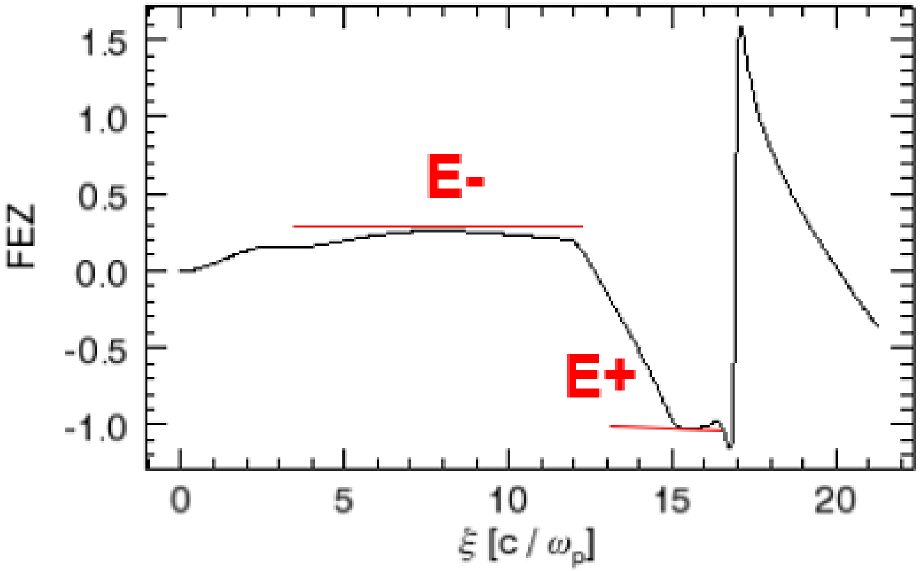
What is High Transformer Ratio?



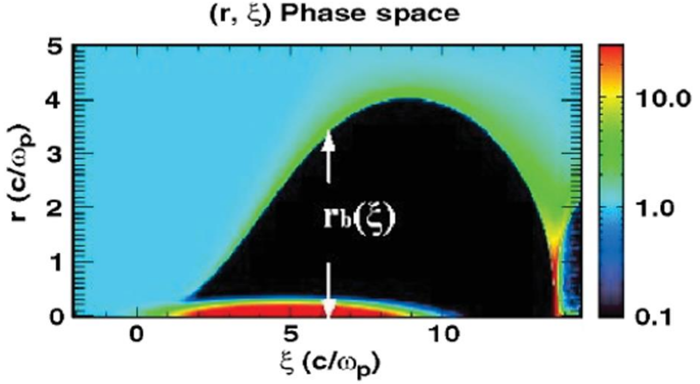
$$TR = E^{+}/E^{-}$$

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

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

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

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

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

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

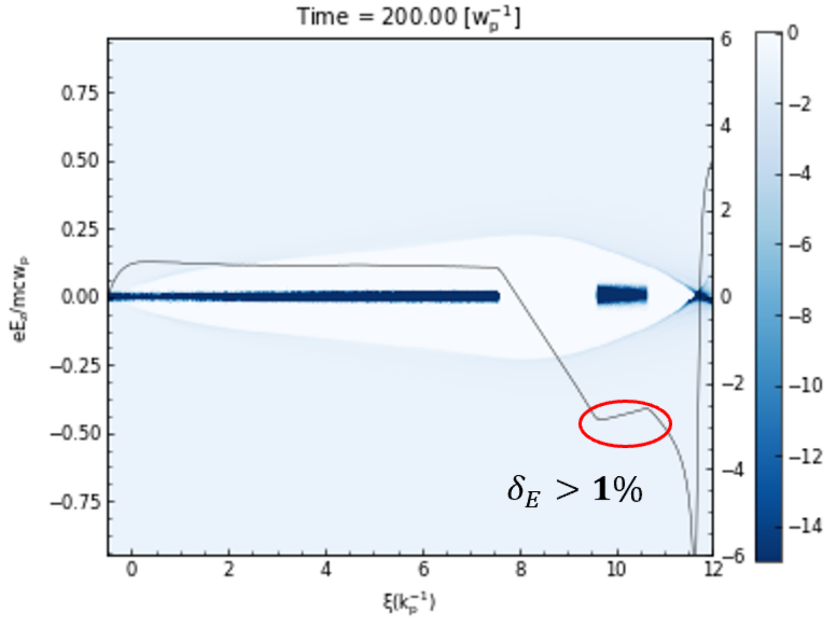
For our case, try to make the TR ≥ 3.55!

Optimize Conceptual Design V2.0

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

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



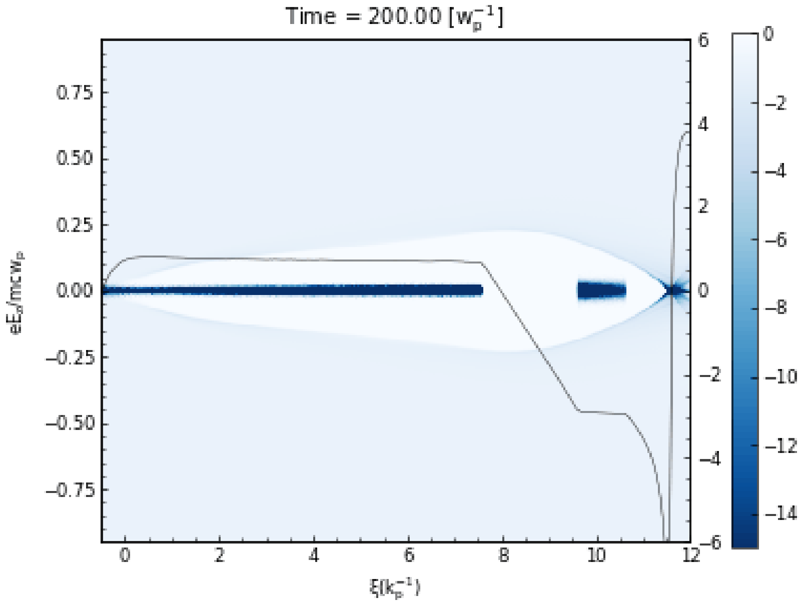
1) **Matched beam → Preserve the emittance**
2) **Ez↑→ Trailer's Energy↑ to 45.5GeV**
3) **Trailer's Q ↓ → Flatten Ez → Energy spread ↓**

Optimized Design—e- Baseline 1.0

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	

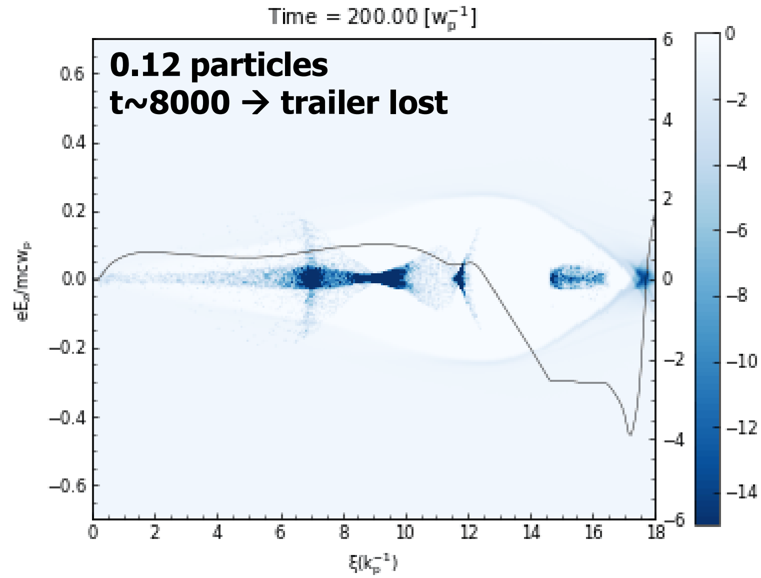
Accelerating distance (m)	10.65
Driver energy $E(GeV)$	1.30
Trailer energy $E(GeV)$	45.5
Normalized emittance $\epsilon_n (mm\ mrad)$	98.44
Charge(nc)	0.84
Energy spread $\delta_E(\%)$	0.56
TR	~ 4
Efficiency (%) (driver → trailer)	59.1

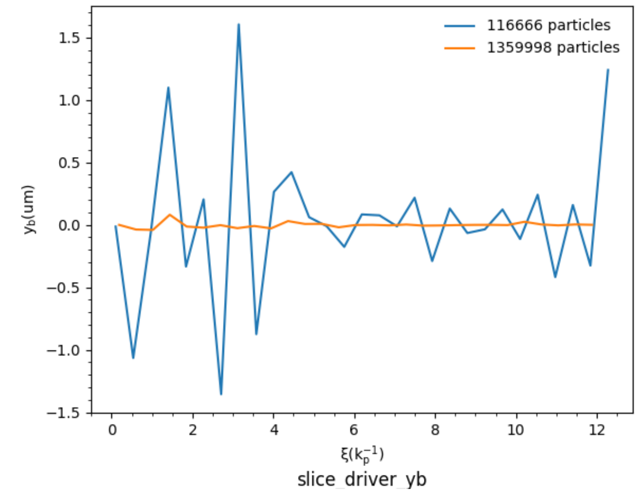
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

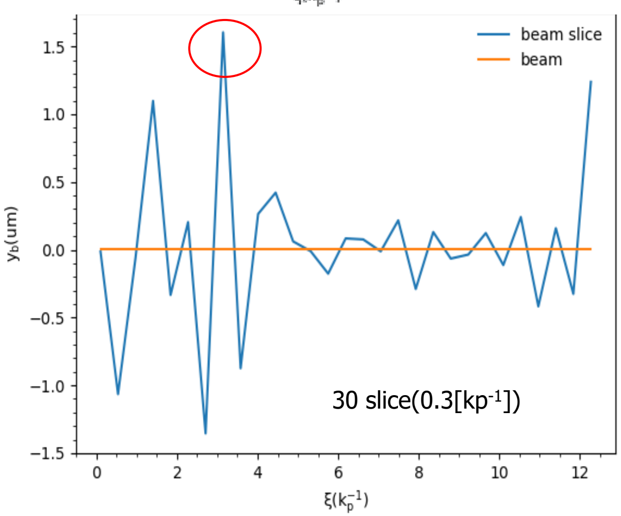


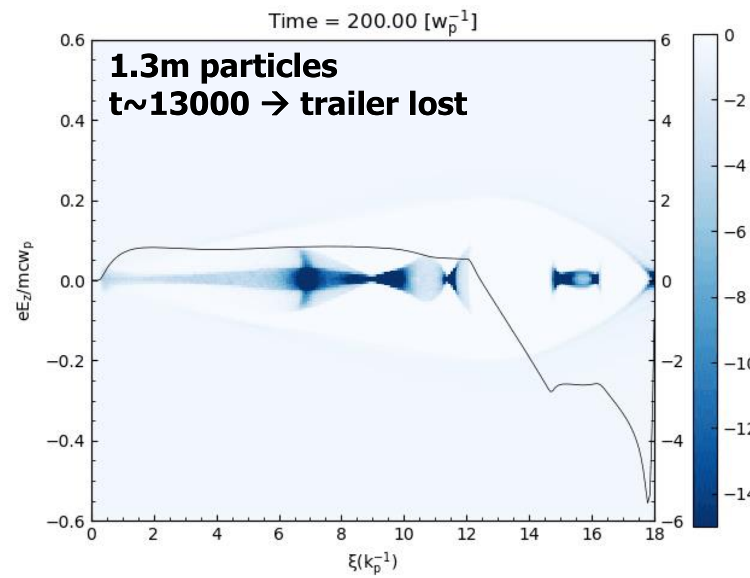
- **10 GeV → 45.5 GeV e- acc. (on paper) work**
- **Much smaller $\sigma_{x,y}$ → Linac difficulty ↑**
- **Trailer's charge close to minimum request**
- **Start studies on real beam & error analysis**

For a “real” linac generated beam





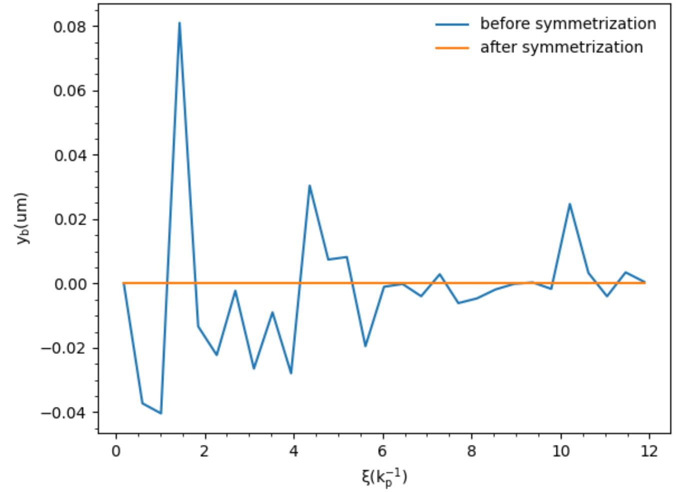


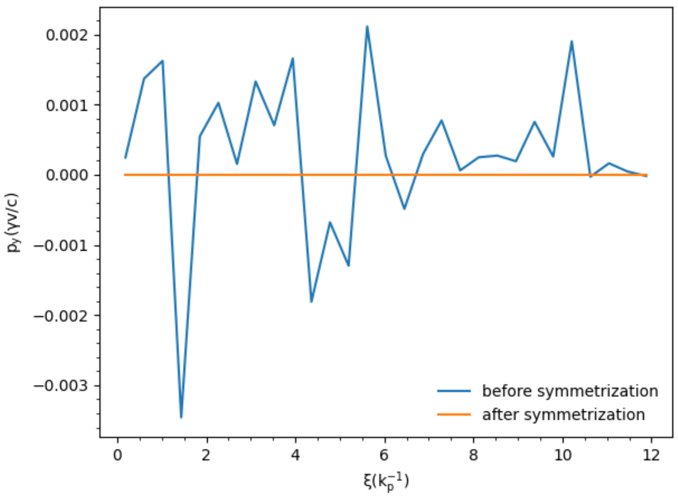


Big slice jitter → Hosing Instability

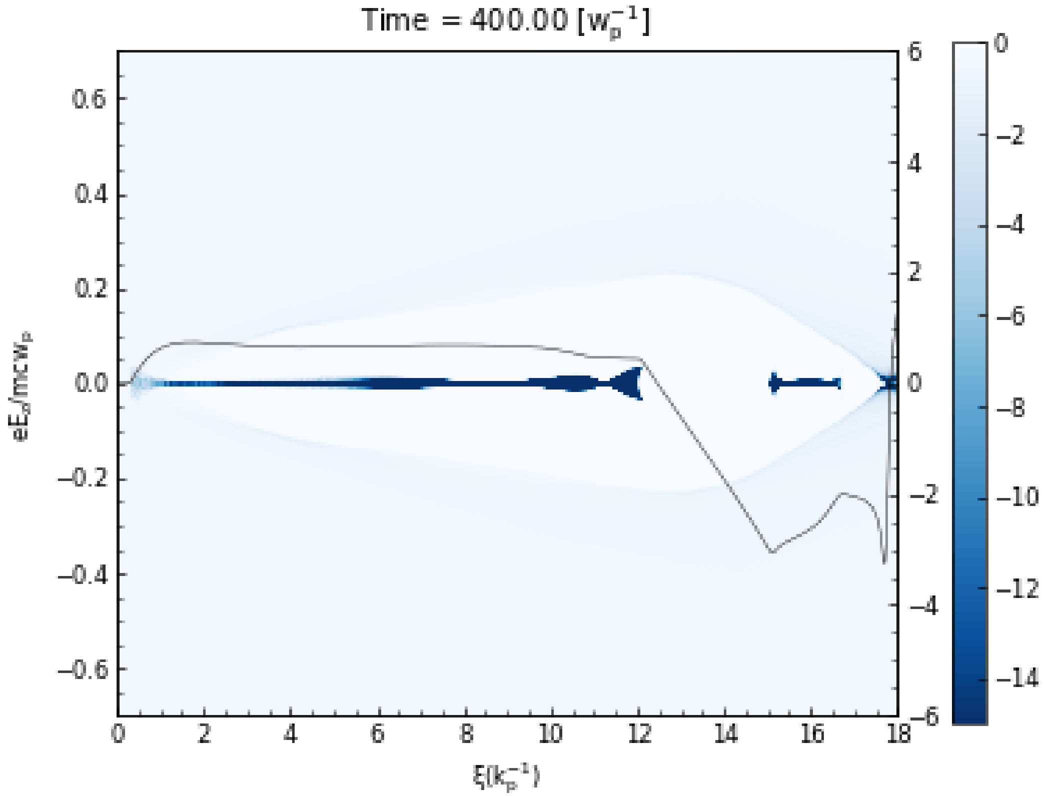
Particle # ↑→ Slice jitter↓ → Hosing ↓

For a “real” linac generated beam





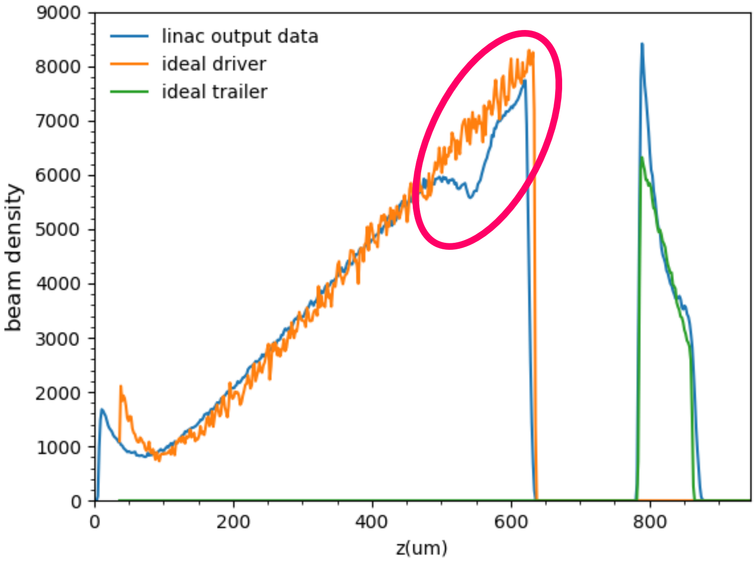
MAKE the beam initial $[x, y, px, py]$~ [0,0,0,0]

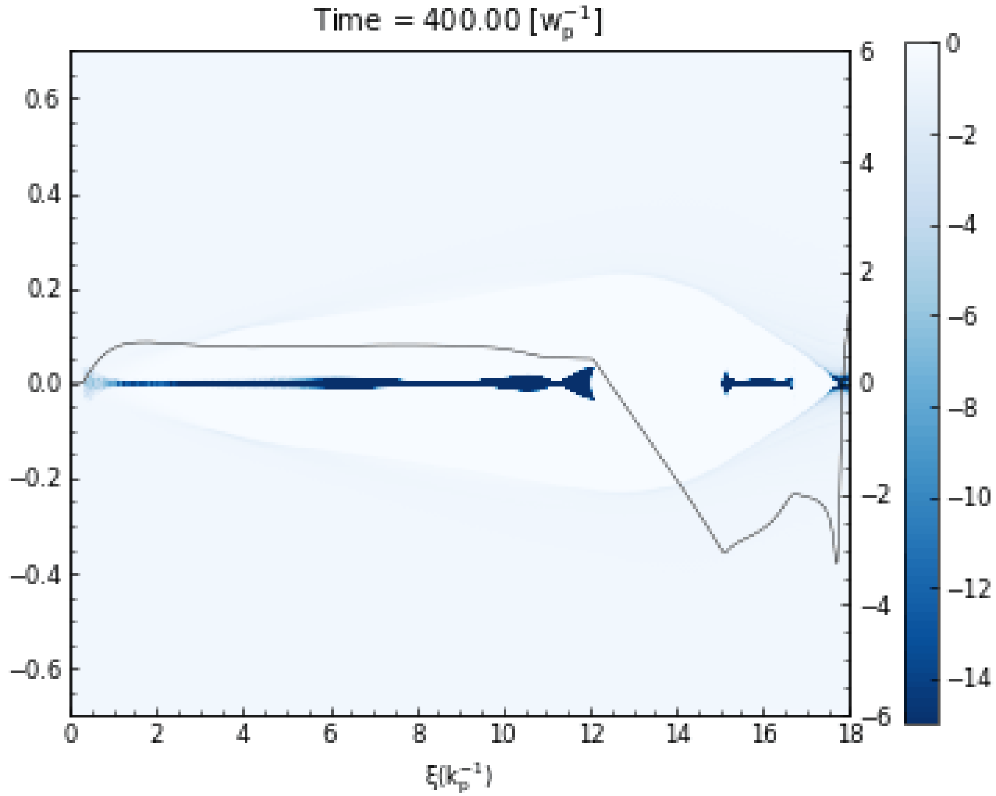


	Symmetry beam	Ideal beam
Et	42.80 GeV	45.5 GeV
Qt	0.7909 nC	0.84 nC

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

For a "real" linac generated beam



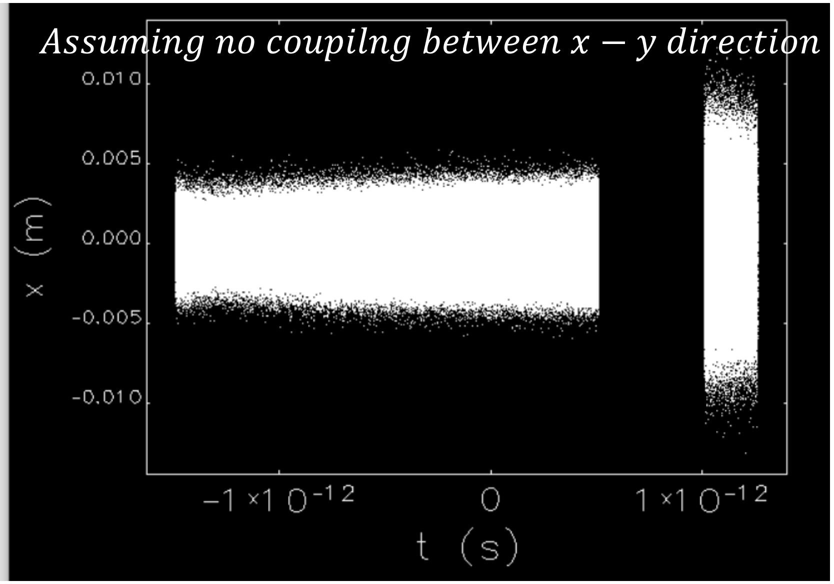


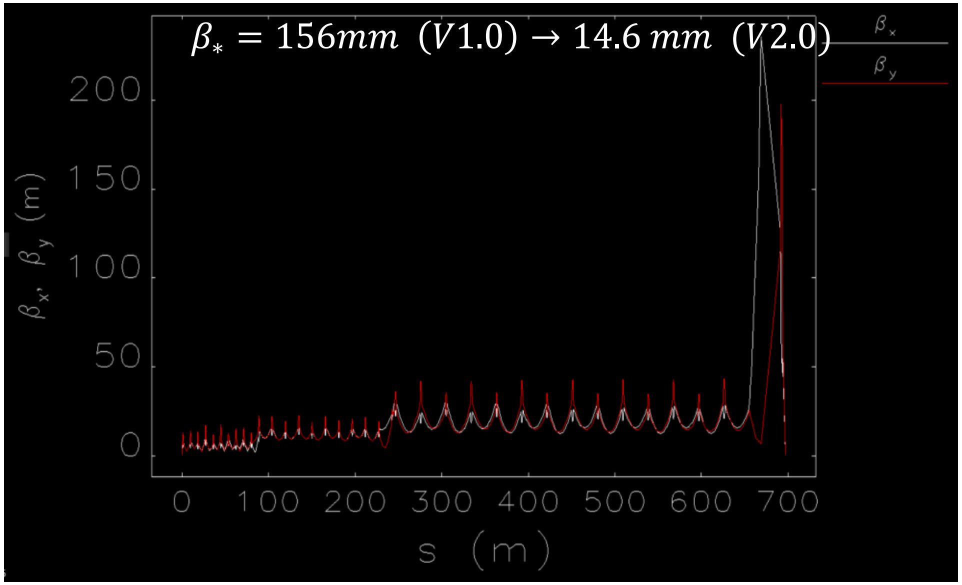
Even assuming the beam is ideal at the exit of e- gun, the beam profile is still not the same as we expected at the linac exit.

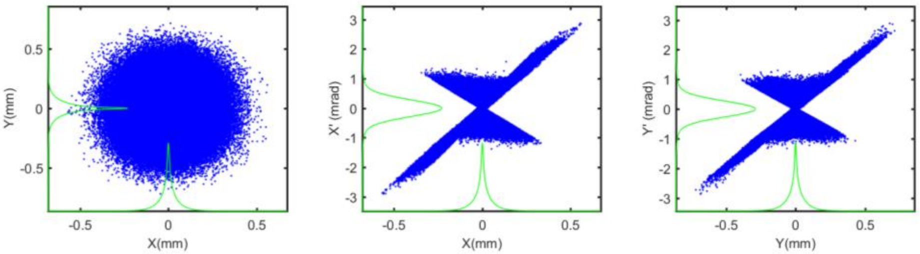
NEED MORE OPTIMIZATION!!

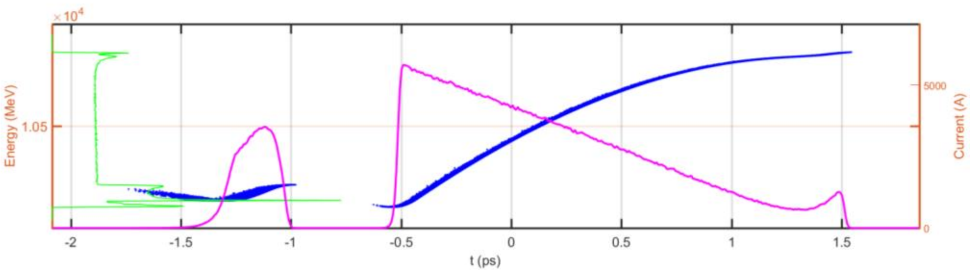
	Symmetry beam	Ideal beam
Et	42.80 GeV	45.5 GeV
Qt	0.7909 nC	0.84 nC

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

Optimized by Dr. Cai Meng (2020)

Error analysis based on ideal beams

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

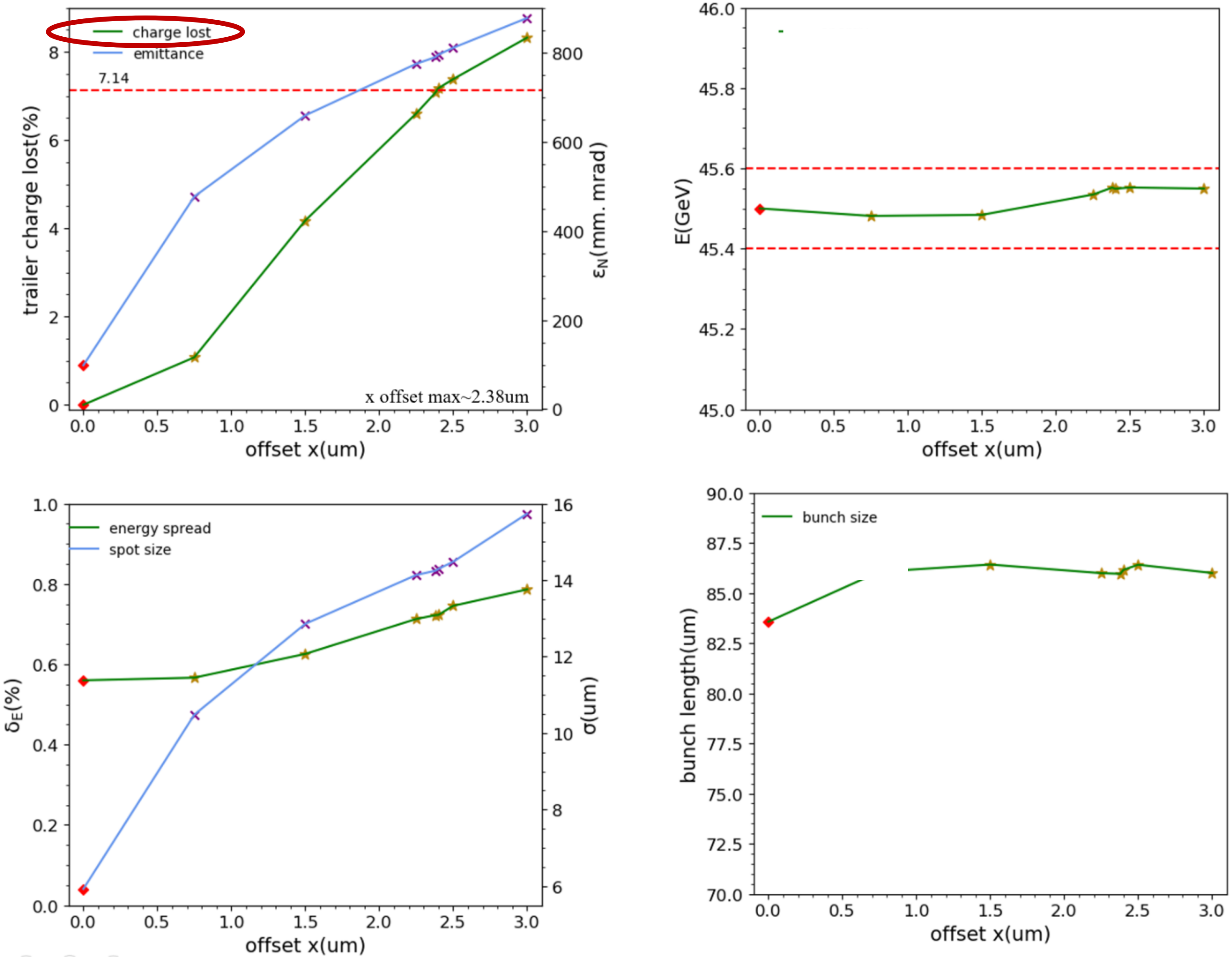
Simulation performed by Dr. X. N. Wang and Prof. W. M. An (2020)

Error analysis based on ideal beams

Perturbation			Limitation	limiting factor	Linac simu. data
Centroid offset	Transverse position		±2.38um	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)

Error analysis – transverse offset



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

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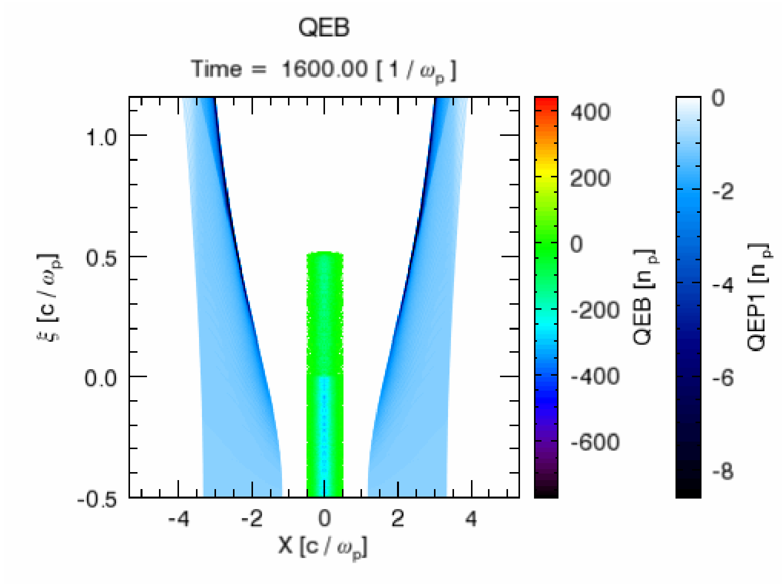
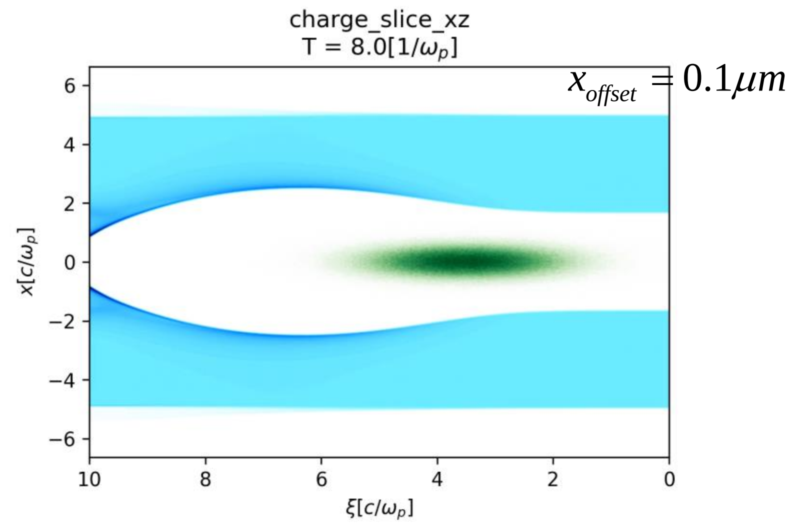
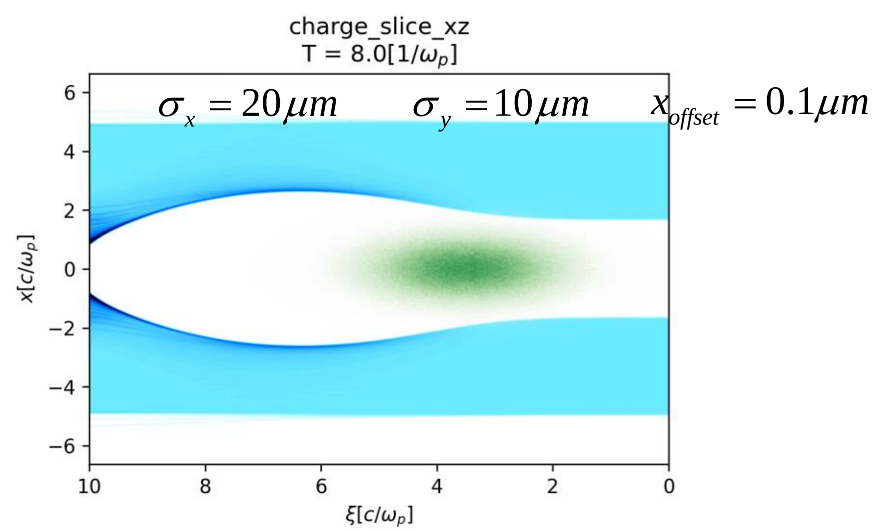
Baseline changed → asymmetry beam



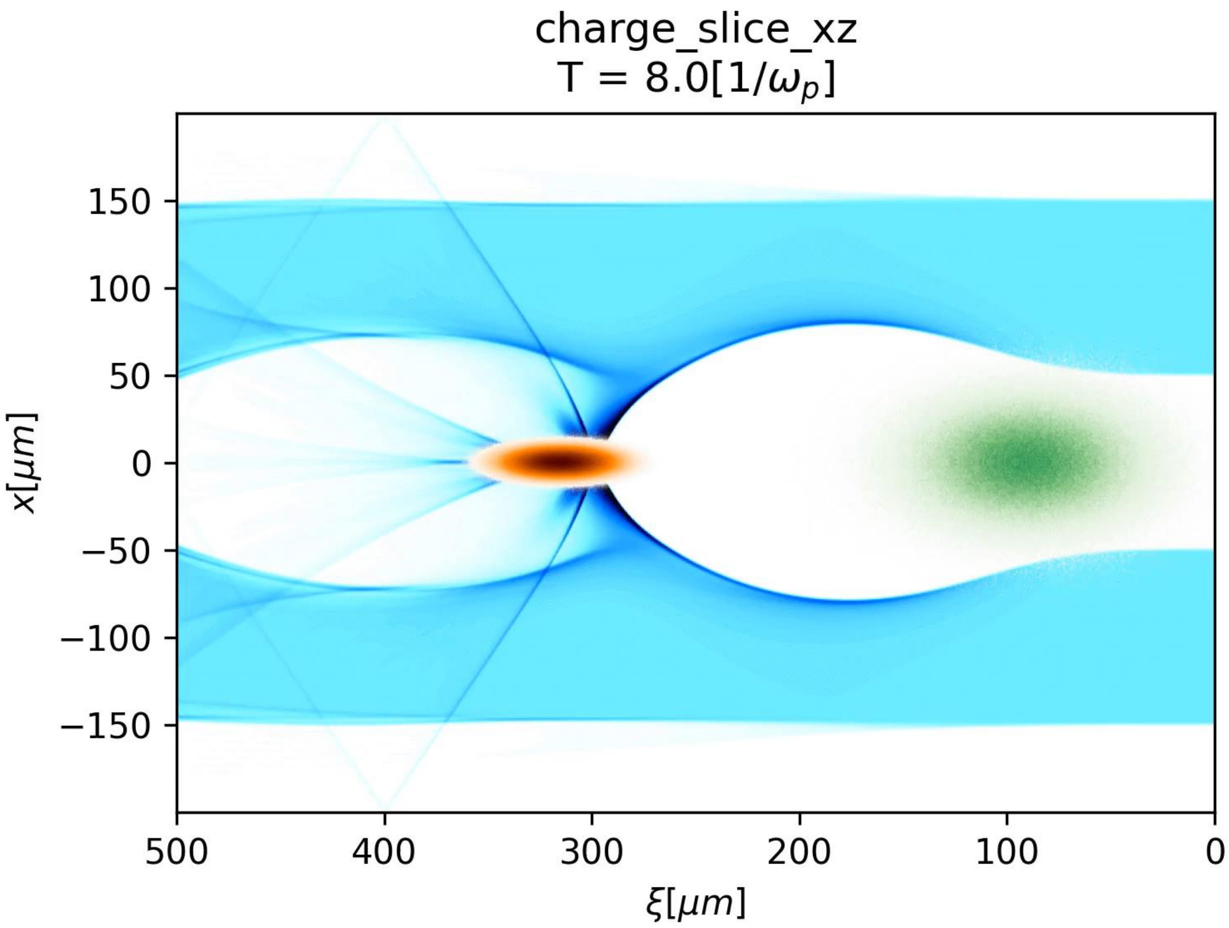




- **High efficiency 60%**
- **Low energy spread ~0.5%**
- **Small emittance growth**
- **Need e- driver, e+ trailer and plasma channel coaxial, not very practical**

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

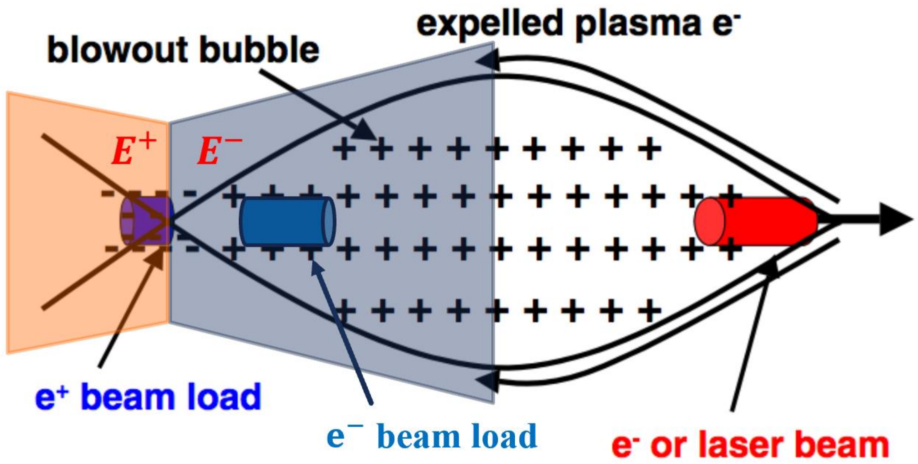
Beam loading helps the acceleration

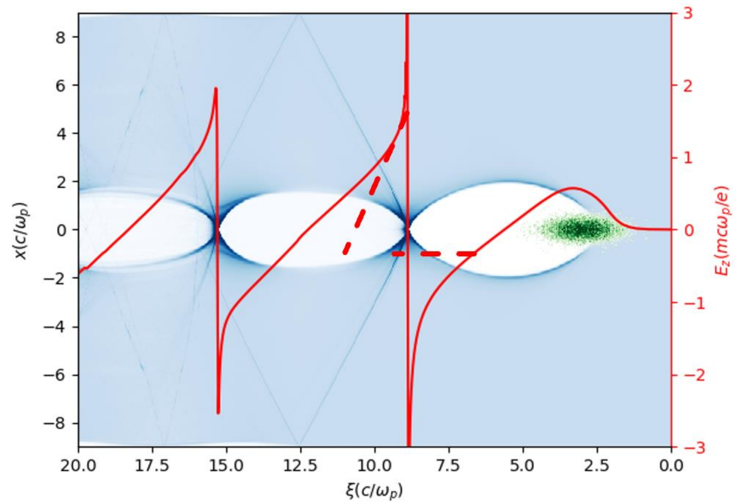


Gradient~5GV/m, Efficiency >30%, Energy Spread~1.5%

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

Basic ideas for improving e+ acc.



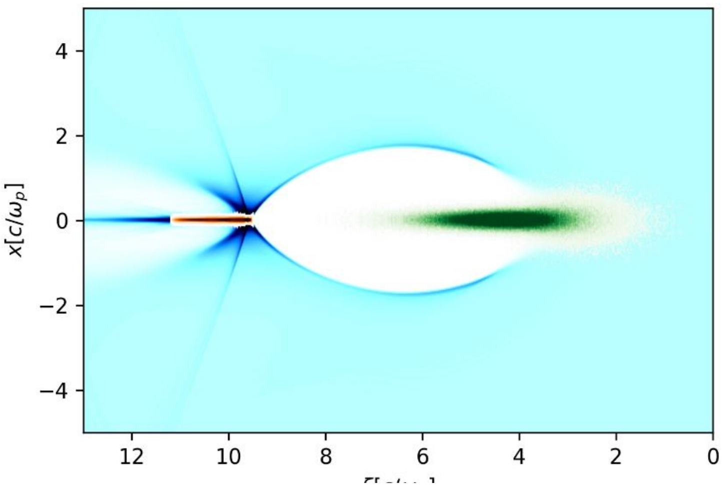


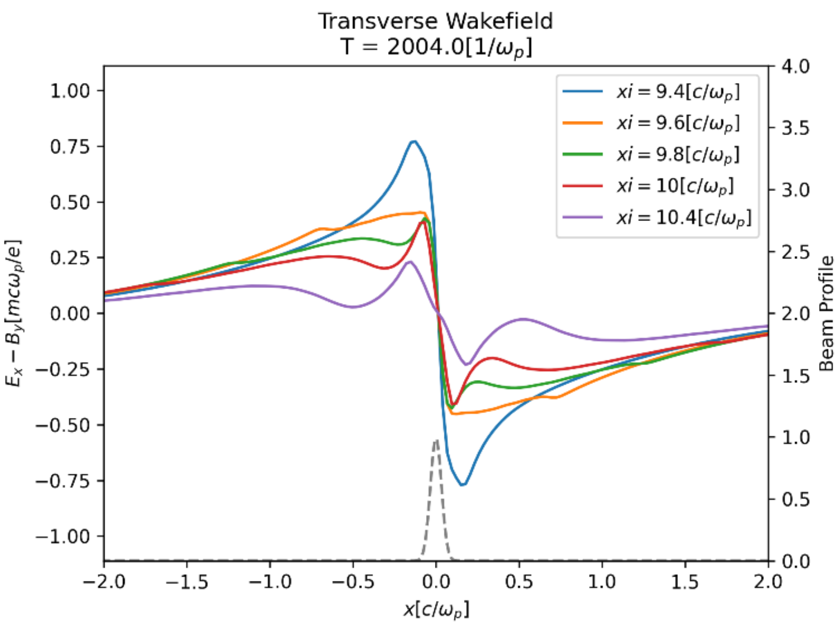
聚焦区域太小

纵向场不适合负载

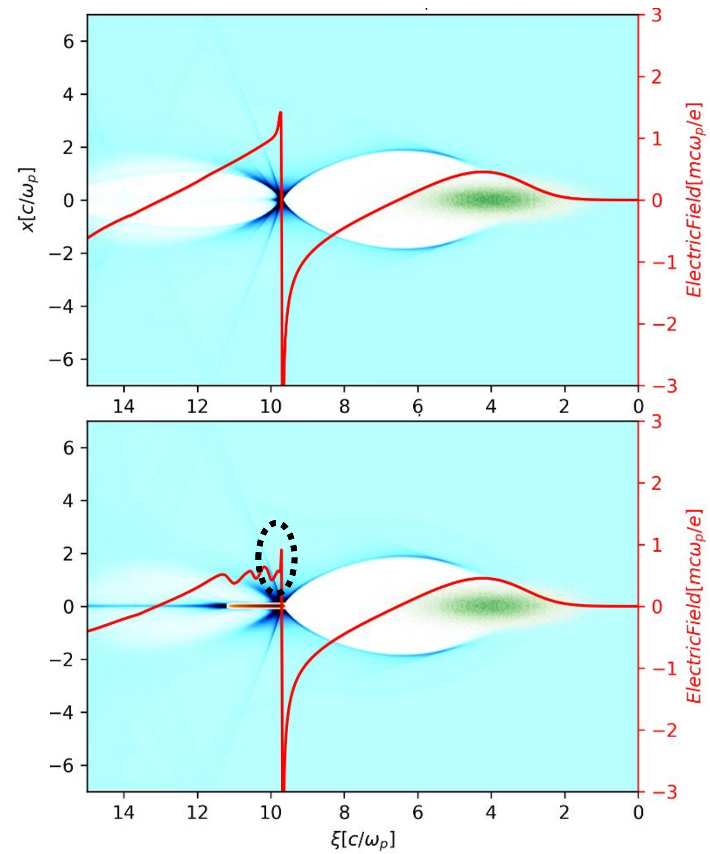
Why plasma wakefield is thought to be unfit for positron acceleration?

On-axis plasma electrons may help

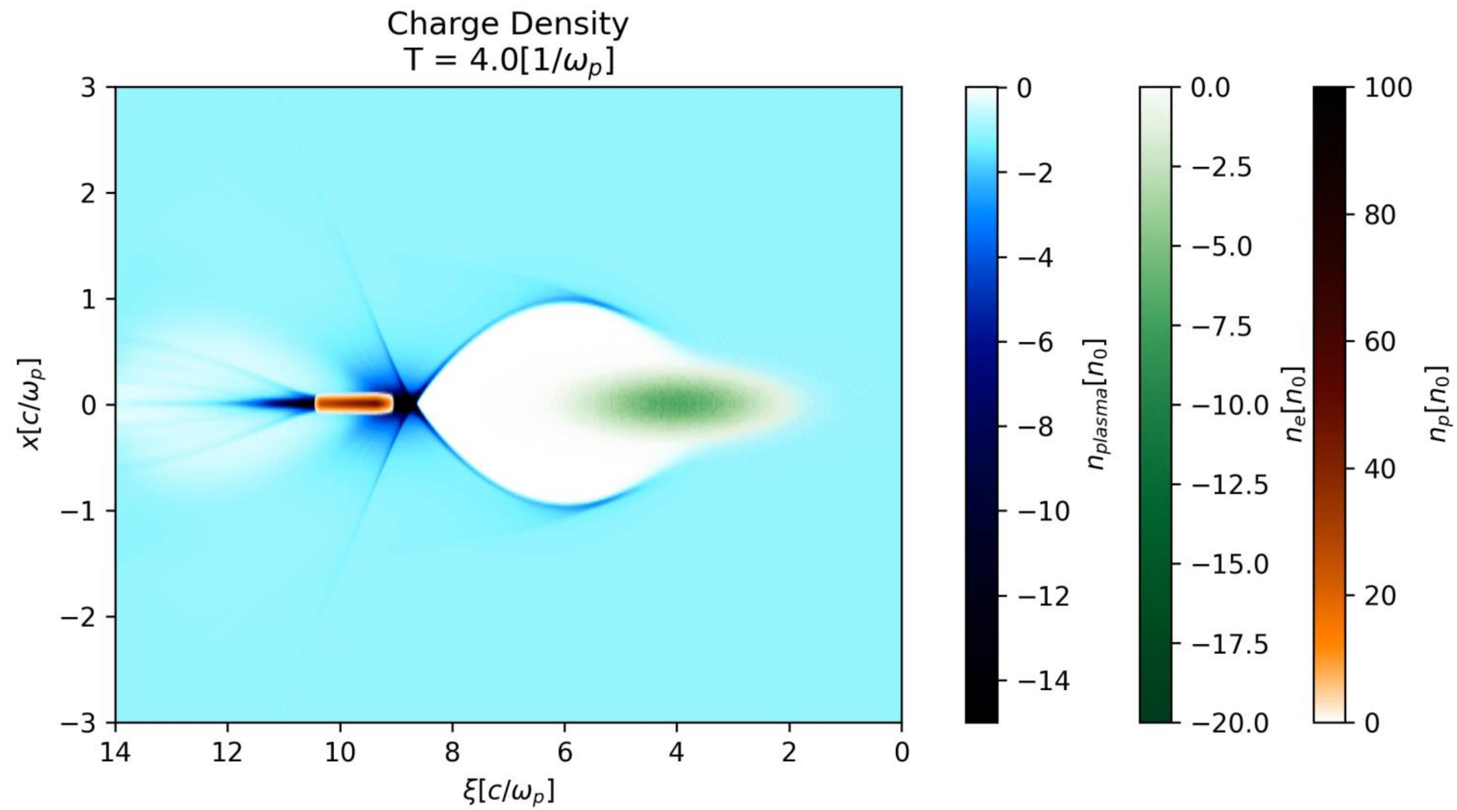




$$E_{z0} = \frac{\partial \Psi_0(\xi)}{\partial \xi} \approx \frac{\partial \Psi_b(\xi)}{\partial \xi} - \frac{1}{2}(n_t + 1) r_t^2 \frac{1}{r_b}\frac{\partial r_b}{\partial \xi}$$



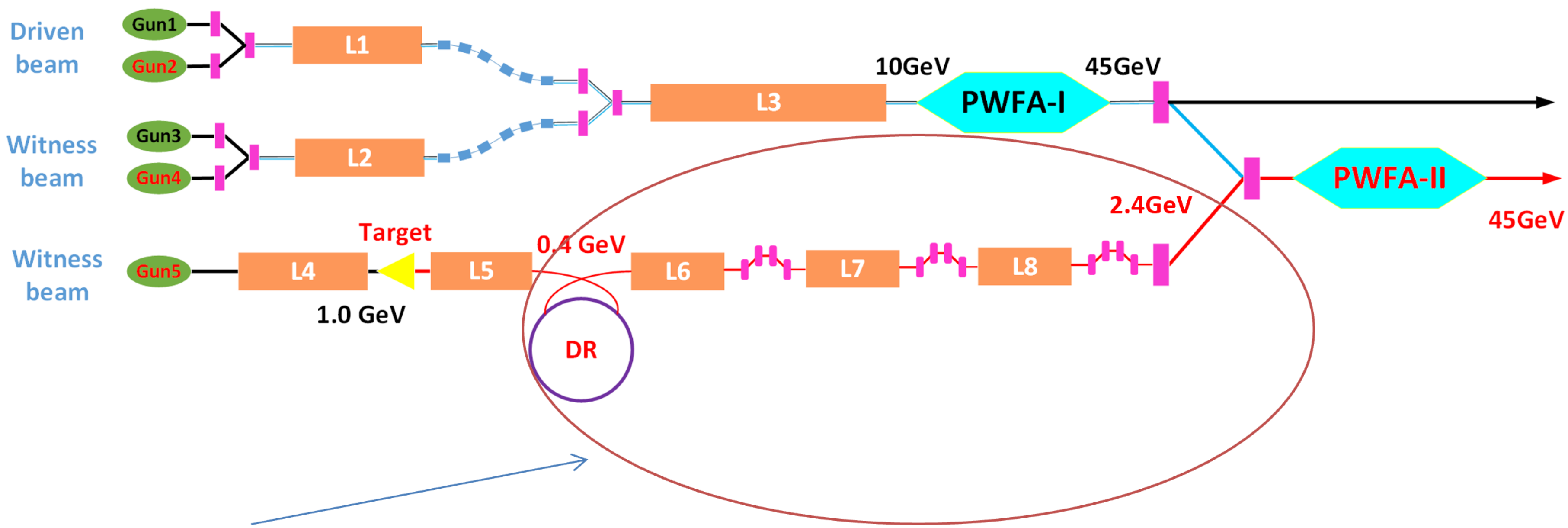
Another successful e+ acceleration



Efficiency ~22%, Energy Spread~1.6% (not well optimized)

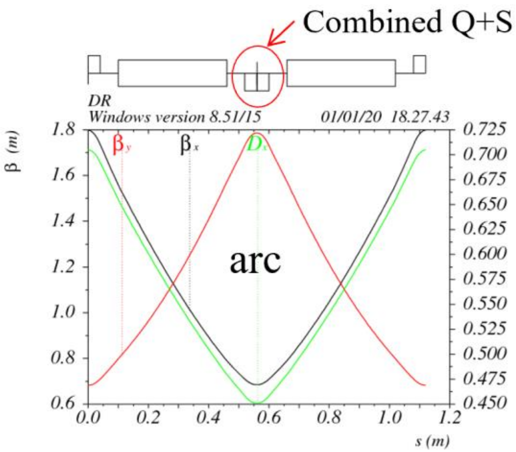
Simulation performed by Dr. S. Y. Zhou and Prof. W. Lu (2018)

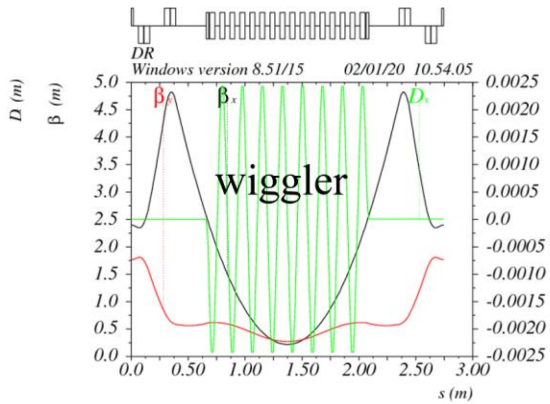
Basic requirement for DR & BC

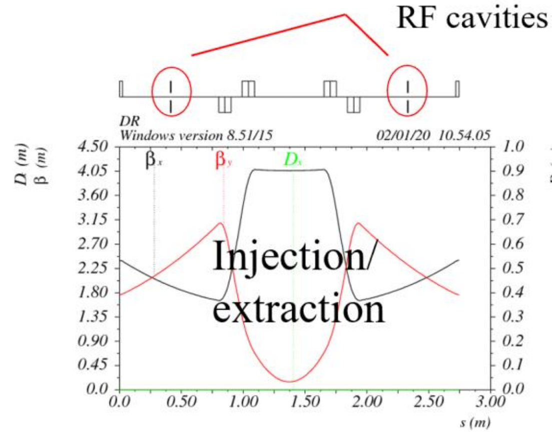


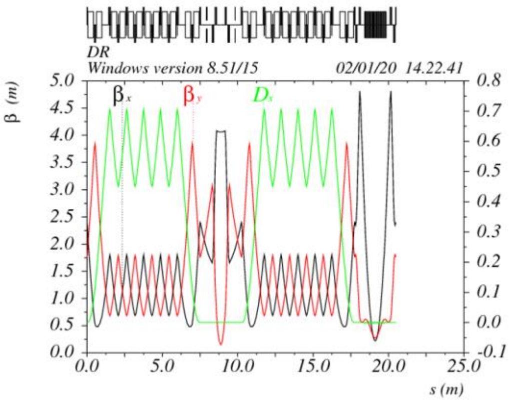
1. Transverse emittance cooling: 2400mm.mrad→ 20mm.mrad
2. Bunch compression: 4.4mm → 20um
3. Transverse beam size focus: 2mm→ 20um

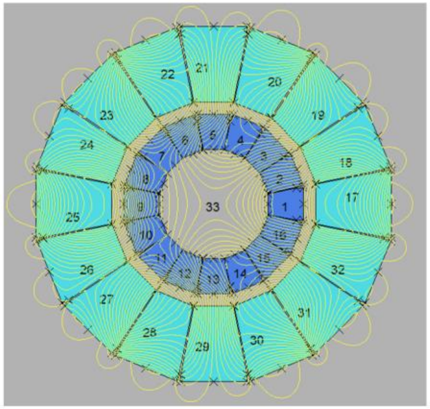
Damping Ring Optics Design V3.0



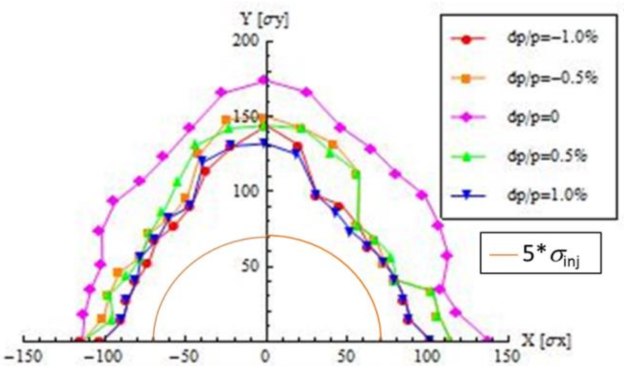








Dynamic Aperture



$\nu_x / \nu_y = 3.16/3.21$

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

Slides from Dr. Dou Wang (2020)

Positron Damping Ring Parameters

	DR V2.1
Energy (MeV)	400
Circumference (m)	20.5
Bunch number	2 (3*)
B0 (T)	0.97
U0 (keV/turn)	5.0
Damping time x/y/z (ms)	10.9/10.9/5.4
δ0 (%)	0.054
ε0 (mm.mrad)	11
Nature σz (mm)	4.3
Extract σz (mm)	4.4
εinj (mm.mrad)	2400
εext x/y (mm.mrad)	68/57 (14/9*)
δinj /δext (%)	0.6 /0.054
Storage time (ms)	20 (30*)

Wiggler parameters	
Dipole strength (T)	4.61
Magnetic period (m)	0.176
Total length (m)	1.42
average βx (m)	1.3

RF parameters	
RF frequency (MHz)	500
RF voltage (MV)	1.5
Cavity number (single cell)	2
Energy acceptance by RF(%)	2.3
harmonic	34
Cavity length (m)	0.5

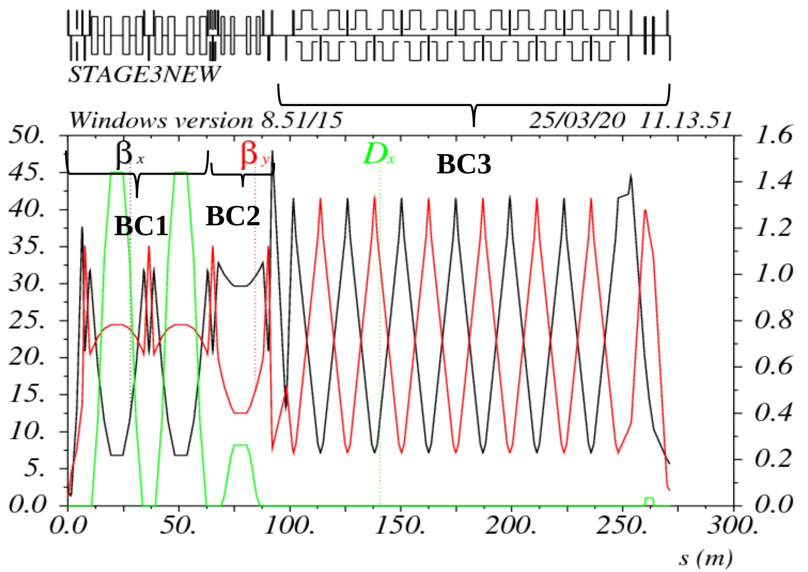
* 120GeV upgrade are taken into account

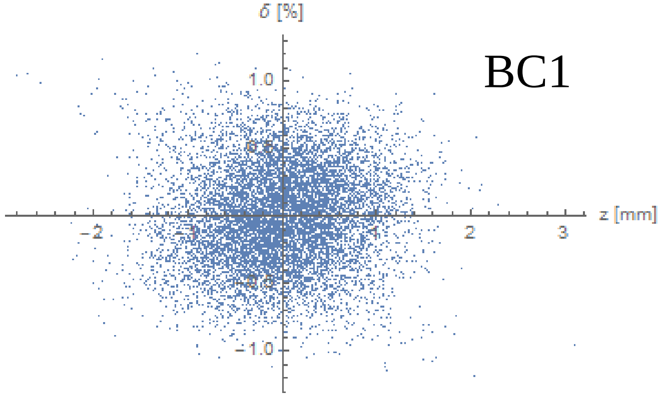
Slides from Dr. Dou Wang (2020)

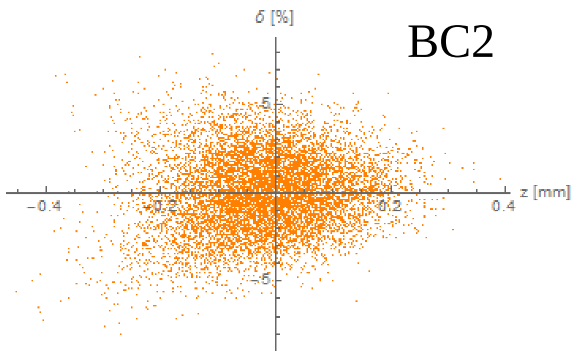
3-Stage Bunch Compressor

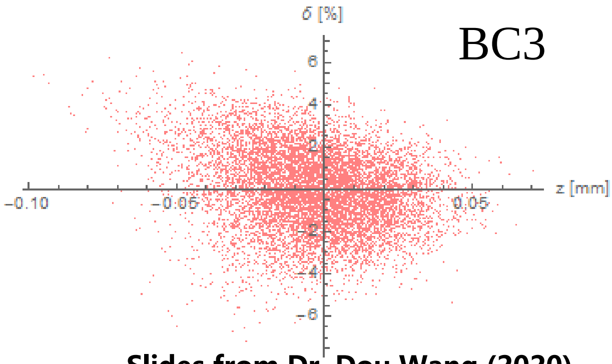
	BCI	BCII	BCIII
Initial energy (MeV)	400	400.1	405
δinj (%)	0.05	0.367	2.17
Initial σz (mm)	4.4	600	100
f_{RF} (GHz)	2.860	5.712	5.712
Voltage(GV)	0.0056	0.12	4.18
Gradient (MV/m)	20	40	40
L (m)	0.28	3	104
ϕ_{RF} (degree)	89	88	61.5
R_{56} (mm)	1200	27.6	5.5
Final energy(MeV)	400.1	405	2400
δext (%)	0.367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





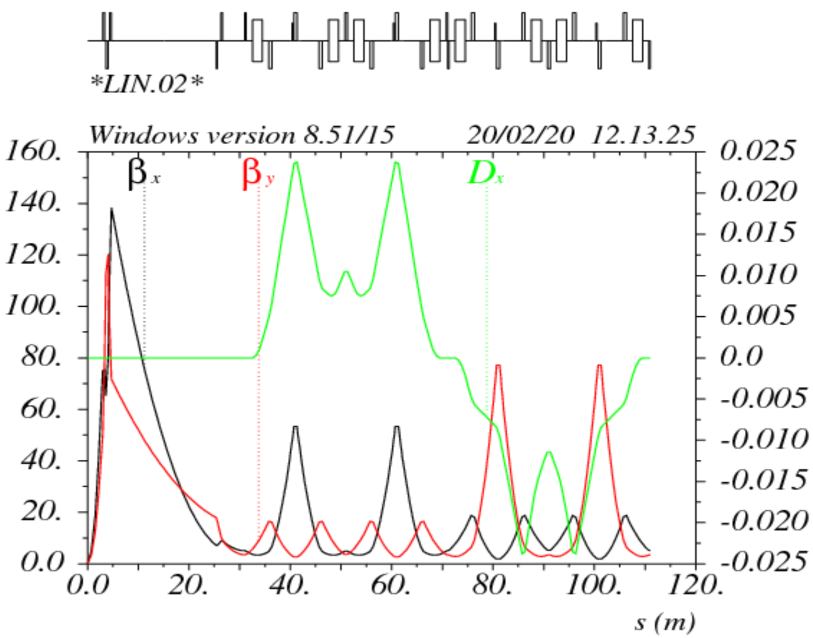


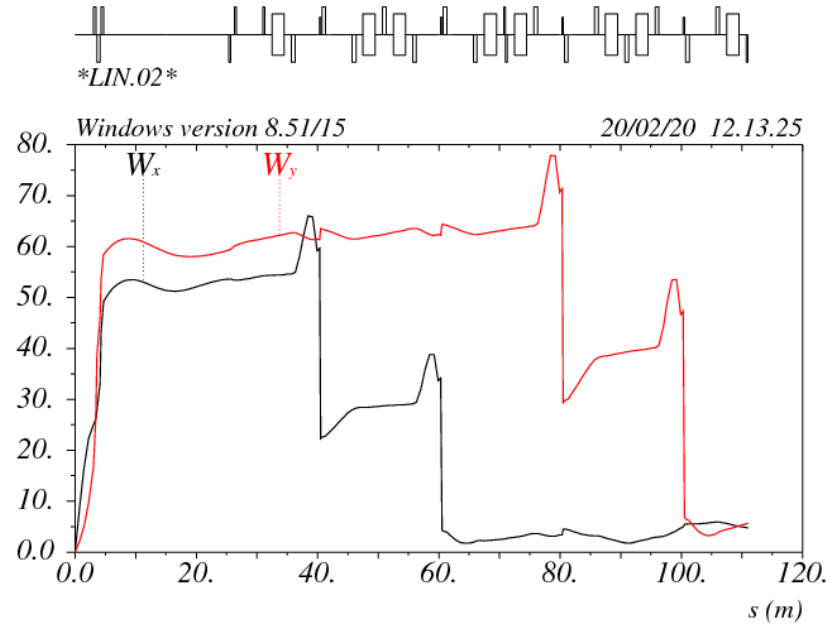


Slides from Dr. Dou Wang (2020)

Positron Final Focus Design

- **Goal**: 20um beam size for horizontal/vertical
- E=2.4GeV, εxn= 15mm·mrad, εyn=10mm·mrad
- L*=3.0m
- βx*=0.12m, βy*=0.18m
- Local chromaticity correction included





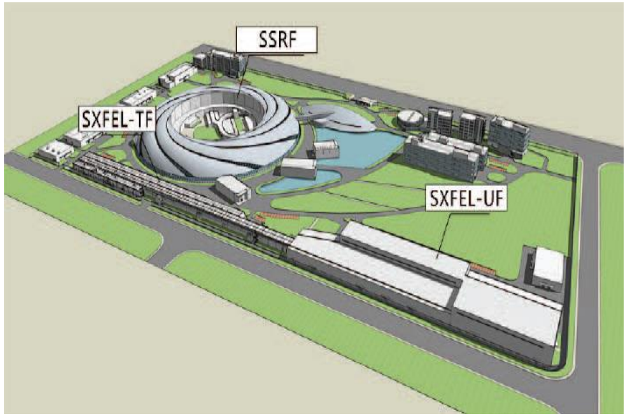
B=87.8Gs, L=2.0m, critical energy=33.6 eV

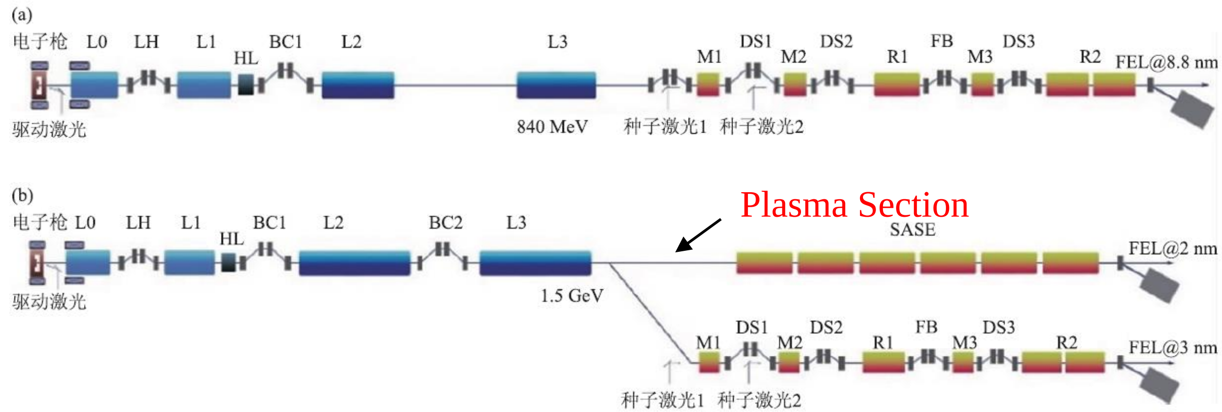
Slides from Dr. Dou Wang (2020)

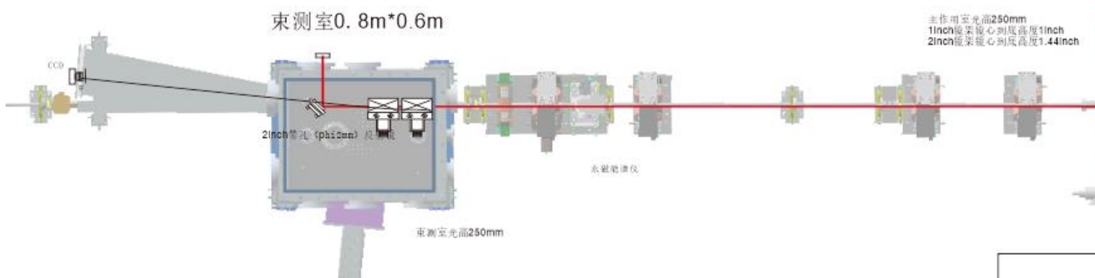
Outlines

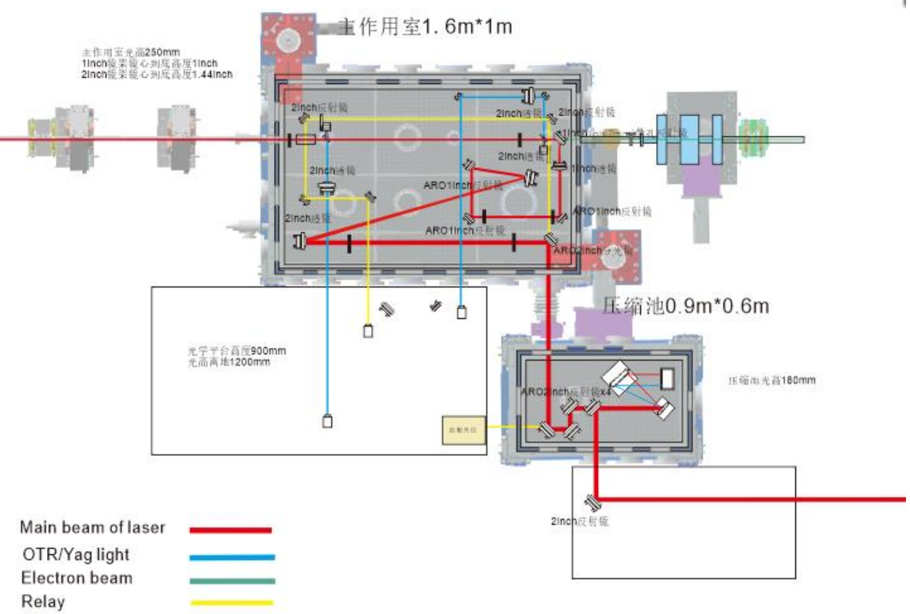
- Introduction
- Recent progress on CEPC plasma injector
  - Linac requirement of CPI
  - High transformer ratio e- acceleration
  - Investigation positron acceleration
  - Performed & proposed experiments
- Summary and prospects

Platform at SXFEL









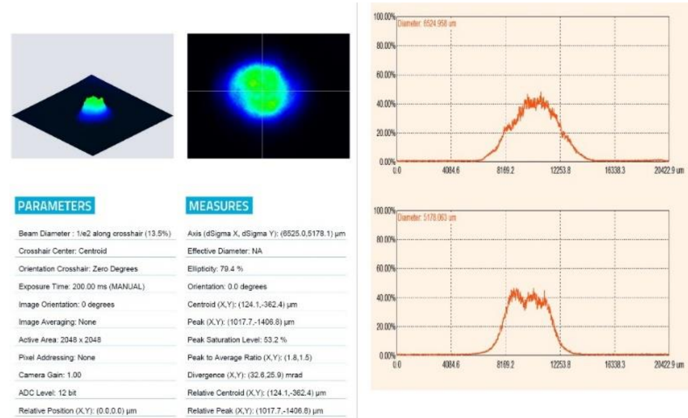
Aim:

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)

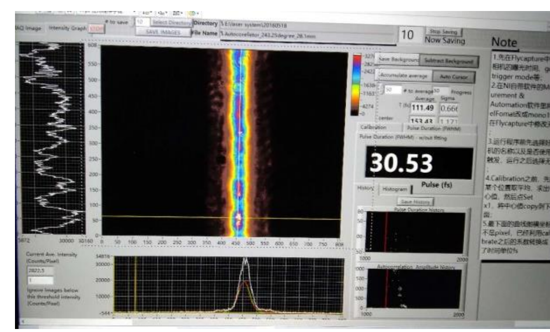
Amplifier energy performance

Amplifier output profile before expander



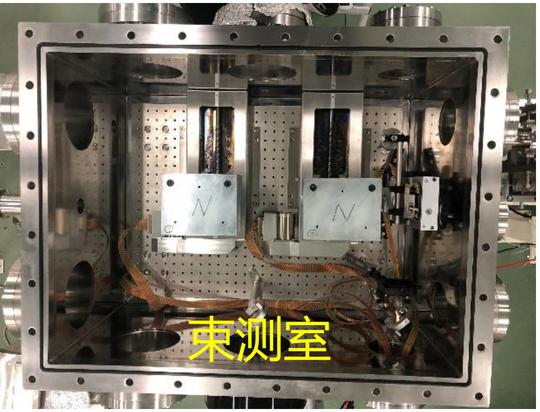
Pulse compressor efficiency: 72%

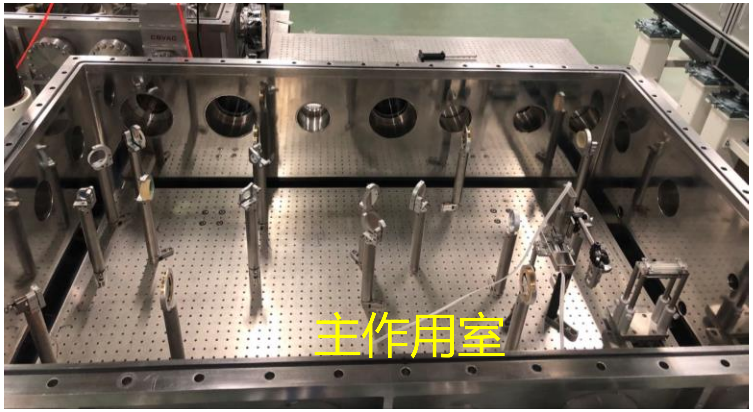
Pulse duration

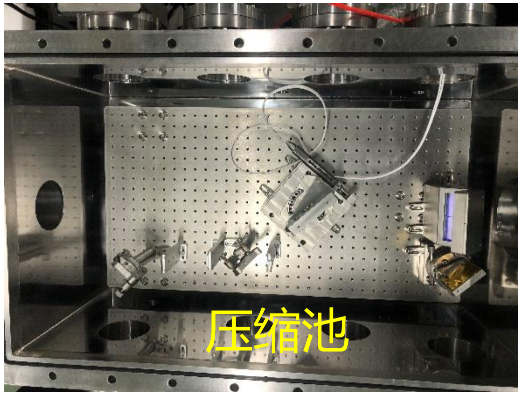


Slides from Dr. Bo Peng (2020)

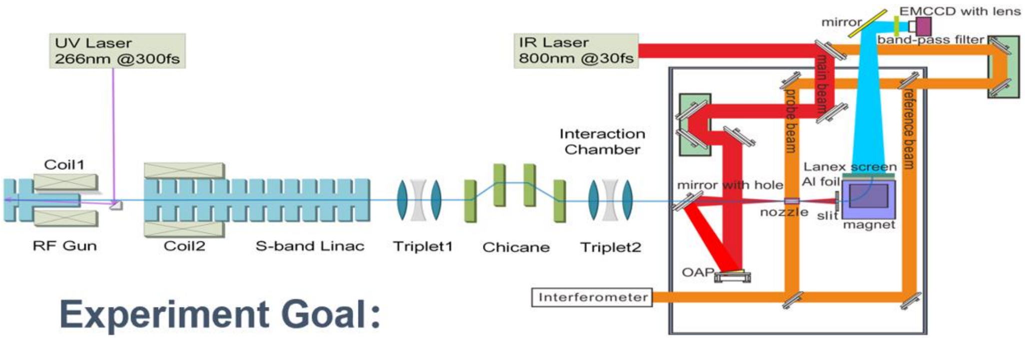
We’re ready (may start 2020.12)





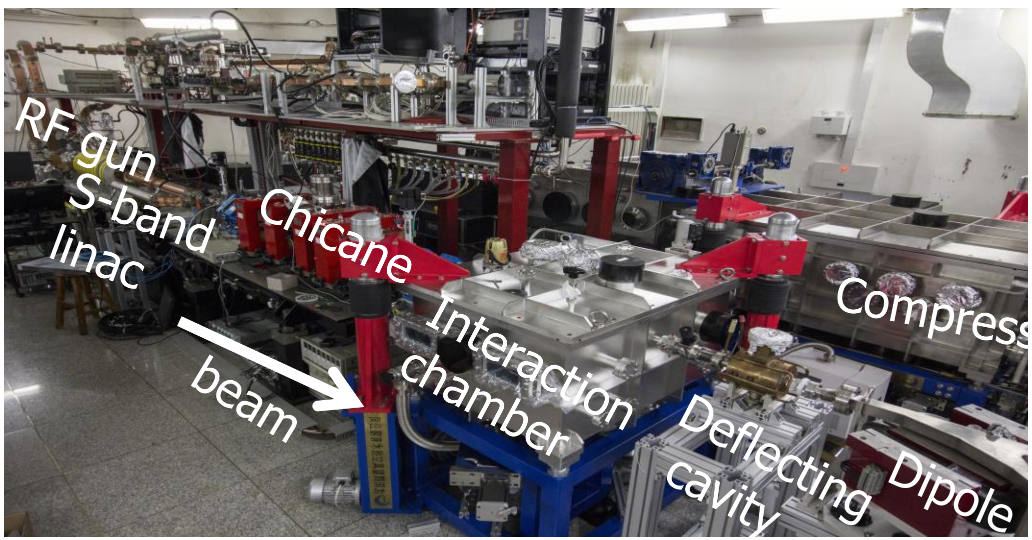


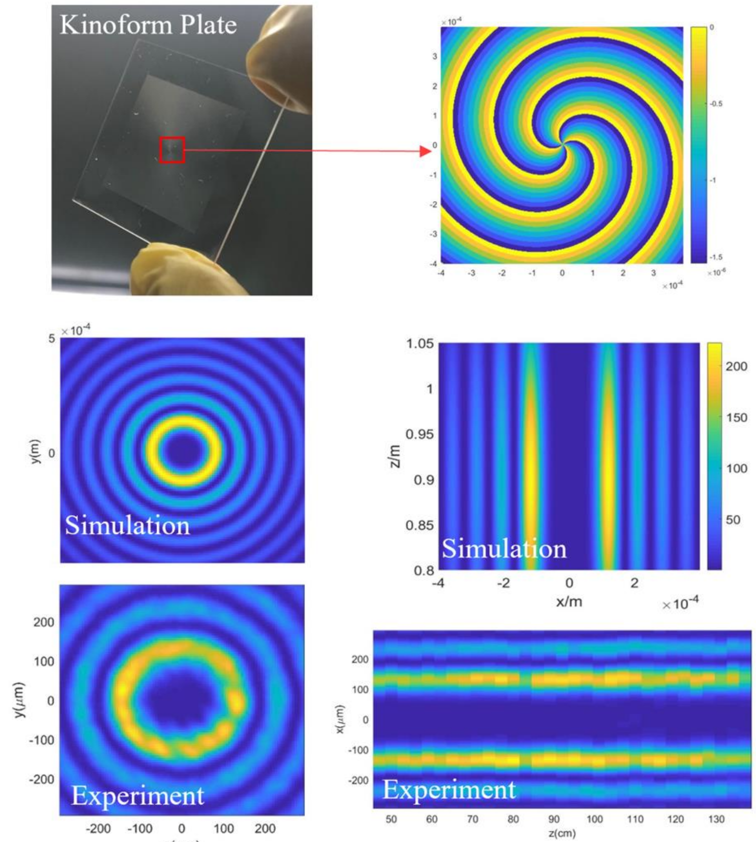
Slides from Dr. Bo Peng (2020)



Experiment Goal:

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



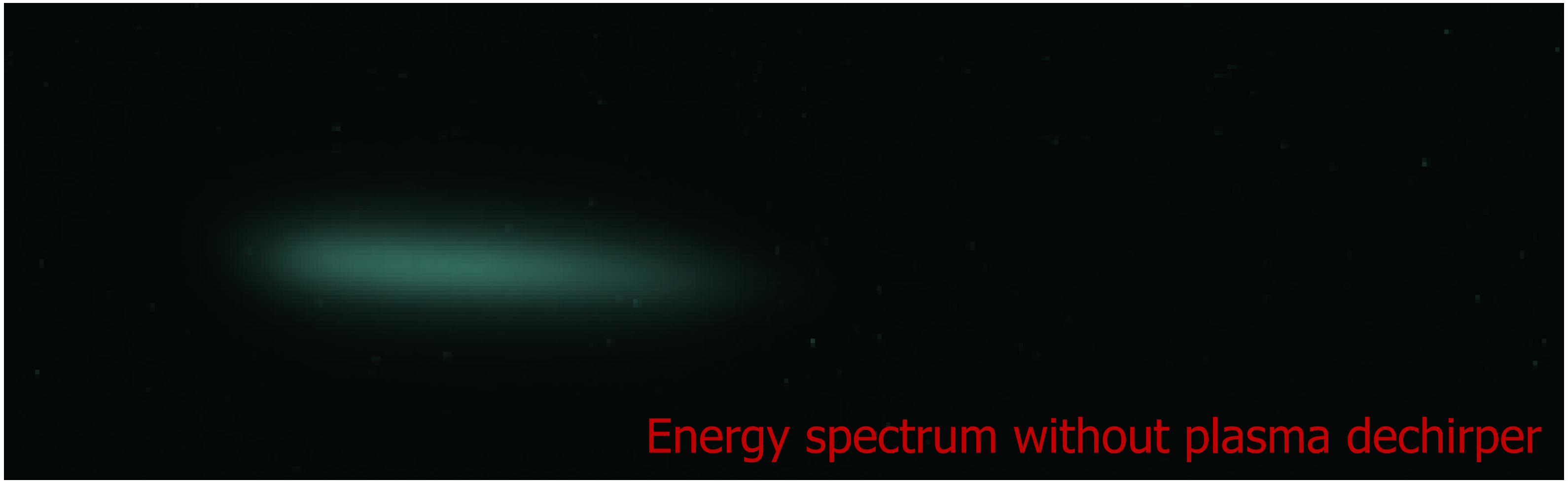


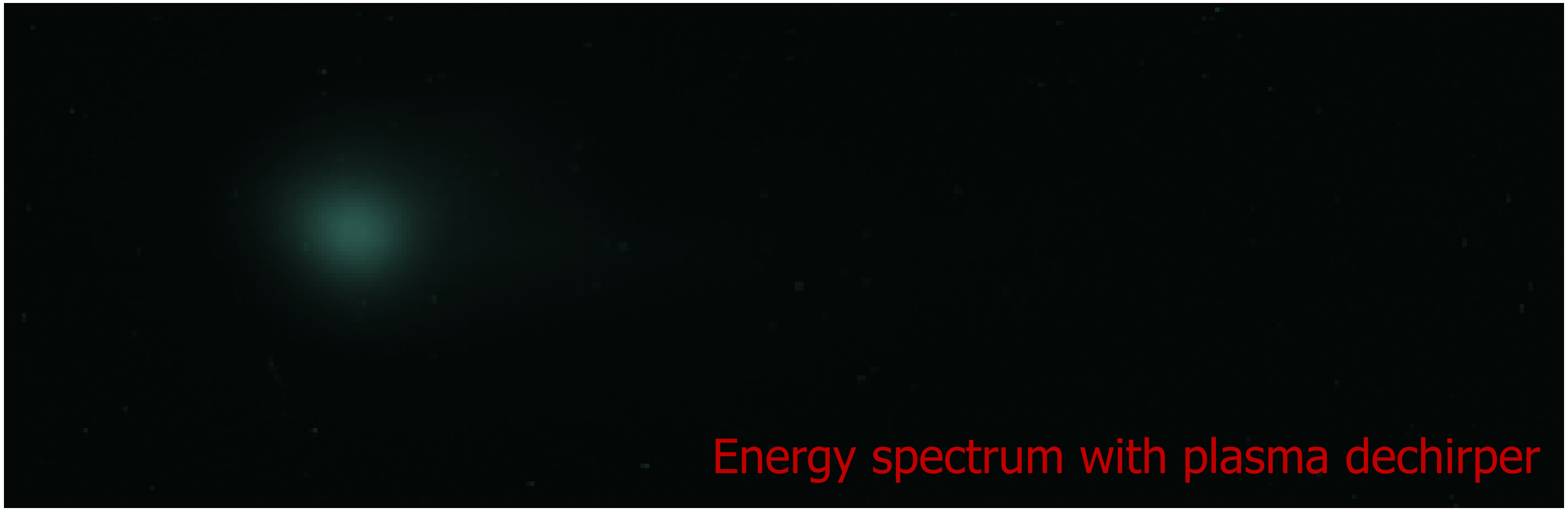
Planned to finish it before February, but delayed by COVID-19.

Re-started last month

Slides from Dr. Shuang Liu (2020)

Some latest raw data from THU lab





Slides from Dr. Shuang Liu (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.

Proposals will be reviewed tonight by SLAC group!!

Outlines

- Introduction
- Recent progress on CEPC plasma injector
  - Linac requirement of CPI
  - High transformer ratio e- acceleration
  - Investigation positron acceleration
  - Performed & proposed experiments
- Summary and prospects

Summary and prospects

- **HTR e- acceleration**
  - Start-to-end simulation performed, linac and CPI requirement updated
  - Detailed error analysis is ongoing, multi-parameter effects are under consideration
  - Linac can not meet the CPI requirement yet, both sides work on it
  - For plasma acceleration, increase the plasma wavelength and lower the TR will be the effective methods
- **e+ acceleration**
  - New methods are studied
  - Fix the baseline parameters at the end of 2020
  - EA and related linac design will start as soon as baseline fixed
- **Experiments affected by COVID-19, but much better now**
  - Test facility for PWFA is crucial and under consideration
- **Feasibility report → CDR → TDR: it's a long way to go**


Thank you for your attentions
Welcome to IHEP, Beijing!