Advanced Accelerator Activities in Asia towards Future Colliders

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Tsinghua University

ALEGRO Workshop at CERN

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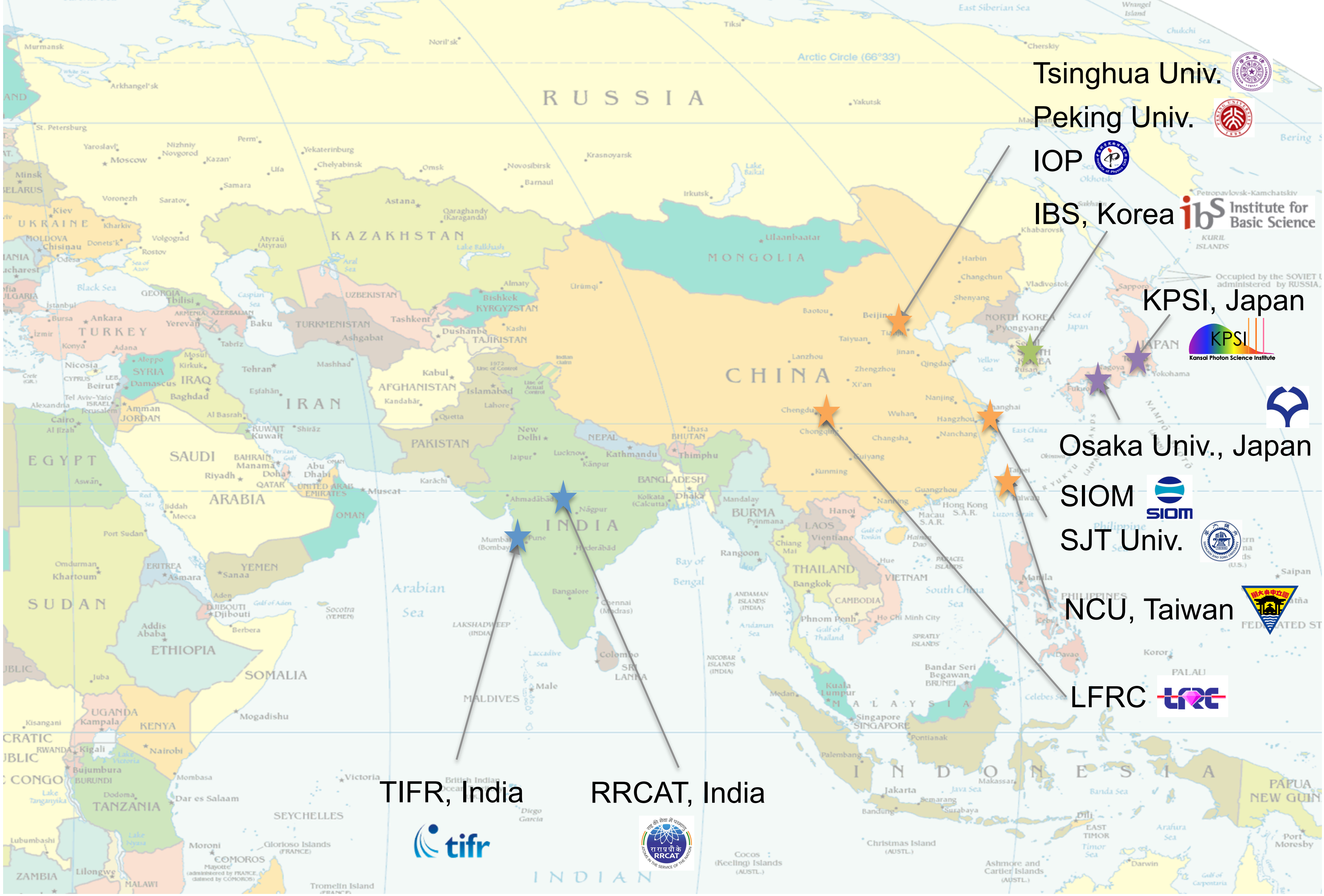
Outline

- AAC relevant facilities in Asia
- Research Highlights
  - **LWFA/PWFA (External injection, energy gain, energy spread, advanced diagnostics, etc.)**
- Future plans relevant to colliders
  - **Plasma based injector for CEPC**
  - **Gamma-gamma collider**
- Summary

Activities of advanced accelerators in Asia



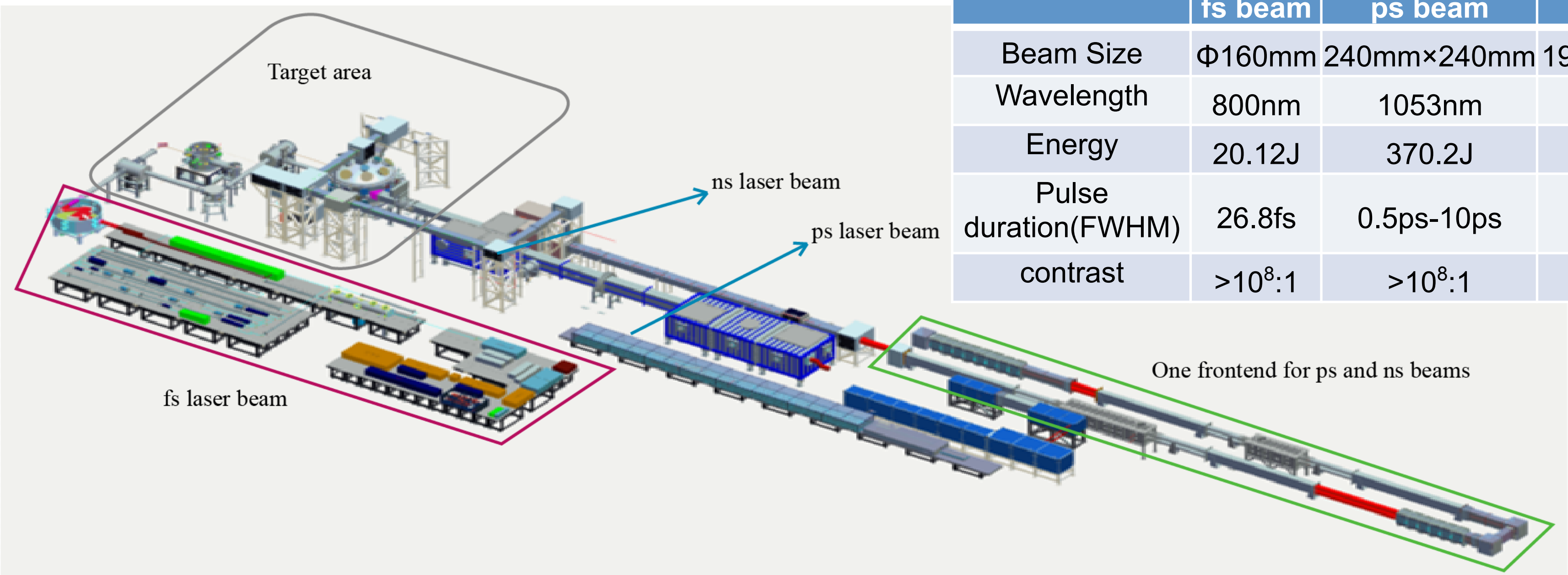
Shanghai Super-intense Ultrafast Laser Facility
(SULF : 10 PW Laser under construction)

Expecting parameters:

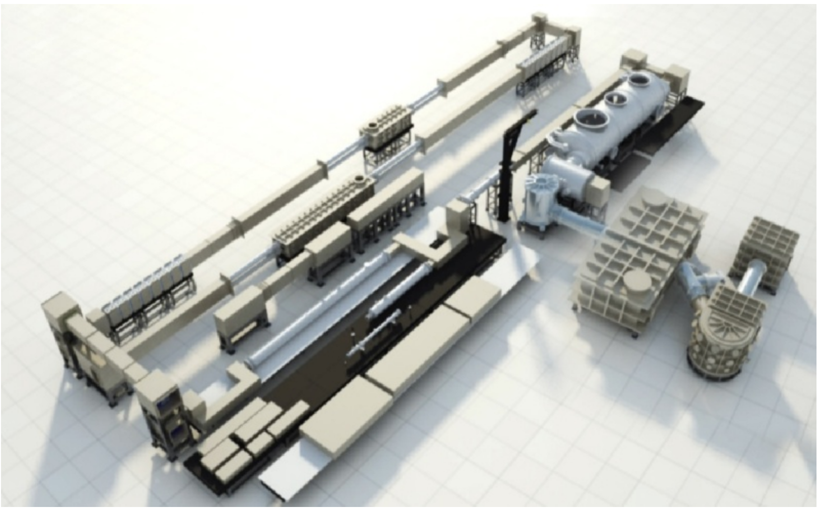
L. P. Yu, et al., Opt. Express., 26: 2625, 2018

- Wavelength: ~800nm
- Pulse energy: ~300 J
- Pulse duration: ~30 fs
- Temporal contrast: ~10^{11}
- Focused intensity: >10^{22}W/cm^2

XG-III 3-pulses and SILEX 5PW facilities



	fs beam	ps beam	ns beam
Beam Size	Φ160mm	240mm×240mm	190mm×190mm
Wavelength	800nm	1053nm	527nm
Energy	20.12J	370.2J	575.4J
Pulse duration(FWHM)	26.8fs	0.5ps-10ps	1.1ns
contrast	$>10^8$:1	$>10^8$:1	/



SILEX 5PW (under construction)

Design parameters:

Wavelength: 800nm

Energy: ~150J

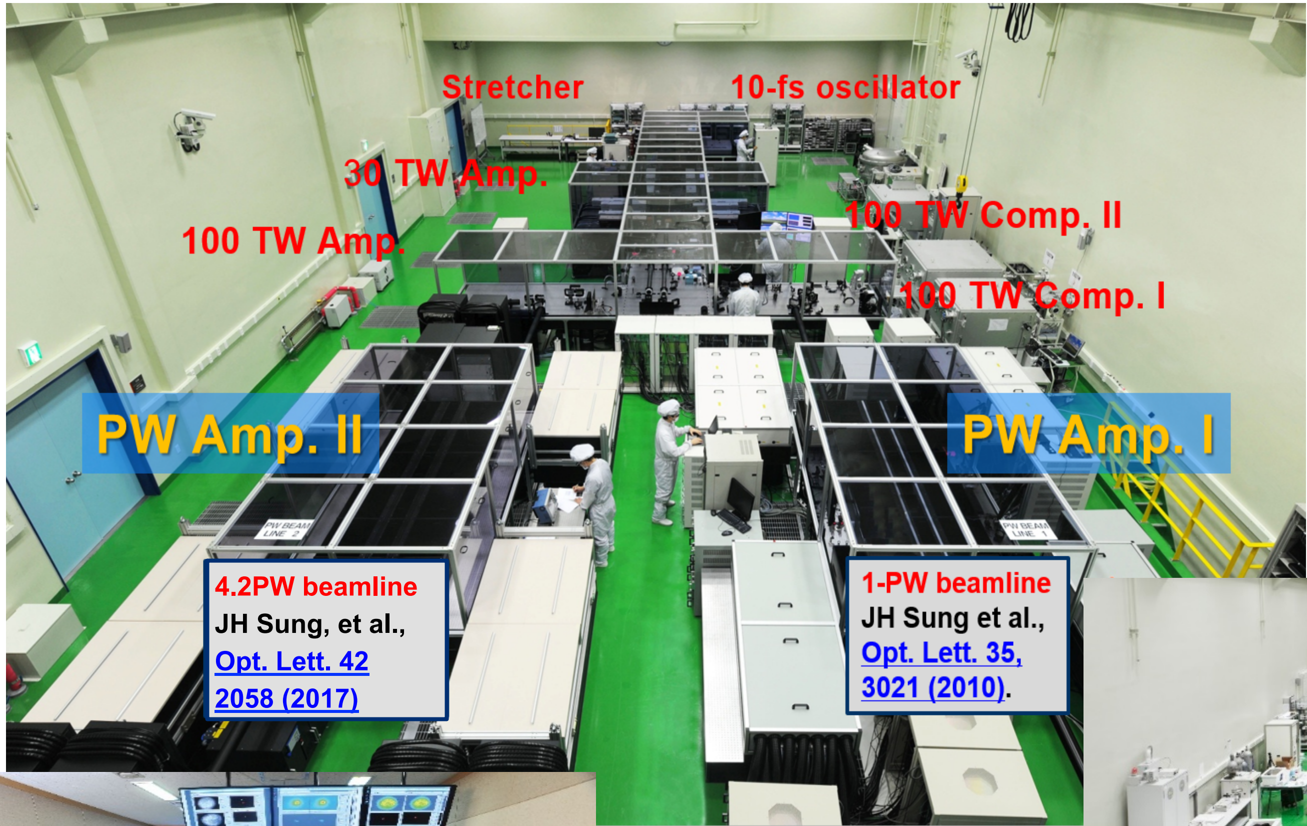
Pulse duration：~30fs

Intensity: $>1\times10^{21}$W/cm^2

Contrast: $>10^{10}$@50ps

4.2 PW, 20 fs laser at 0.1 Hz

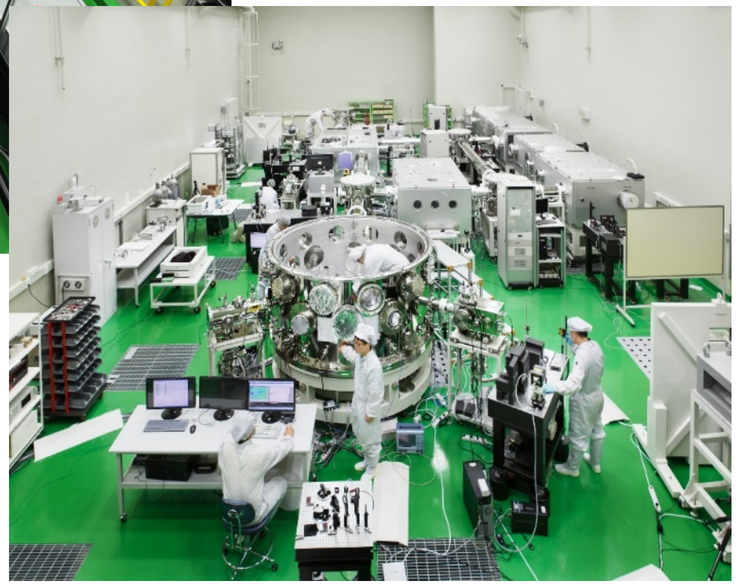
Institute for Basic Science



Beamline I:
30 fs, 1 PW

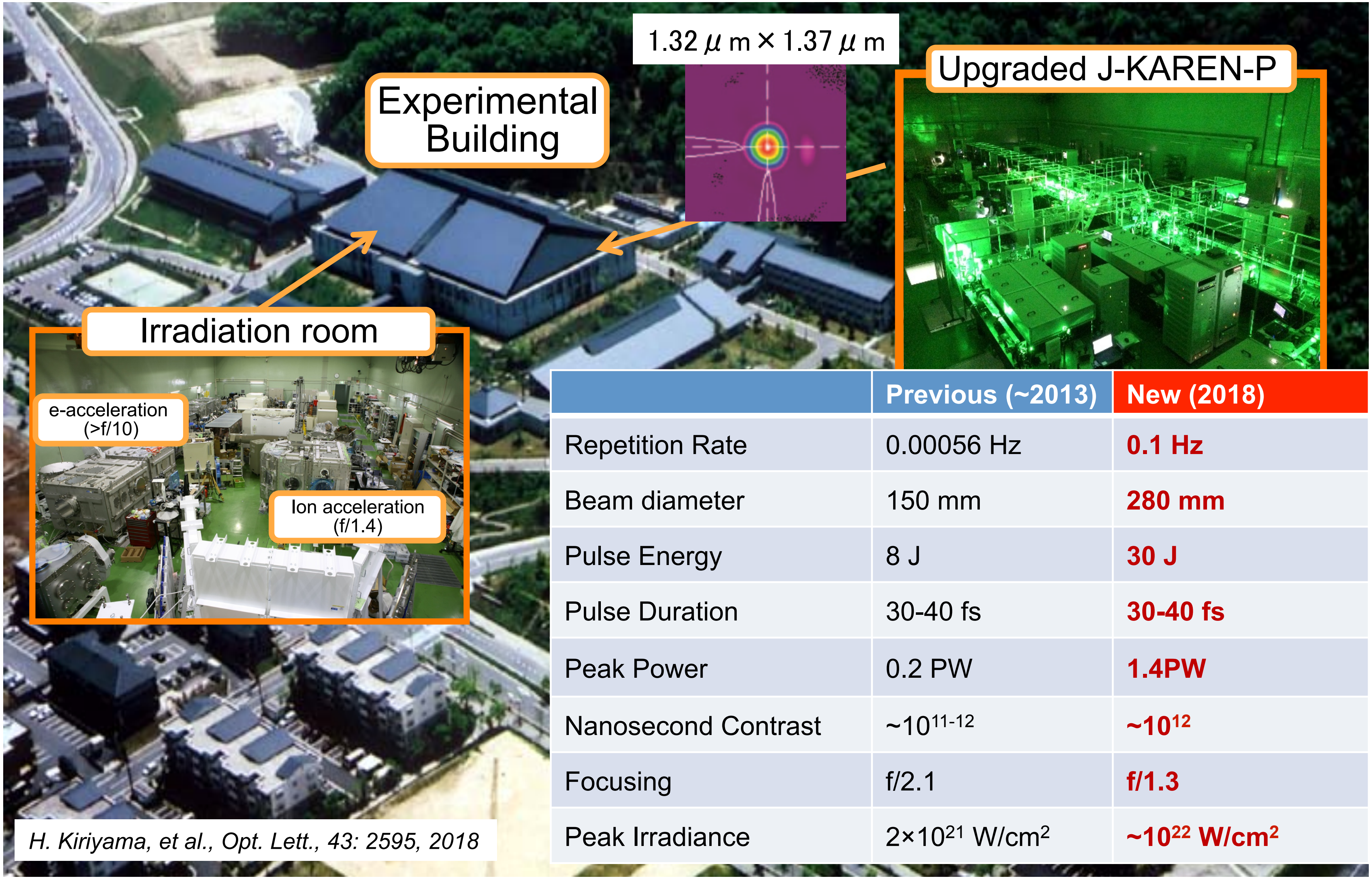
Beamline II:
20 fs, 4.2 PW, 0.1Hz

Control room



PW target chambers

1.4PW, 0.1Hz OPCPA/Ti:sapphire J-KAREN-P



	Previous (~2013)	New (2018)
Repetition Rate	0.00056 Hz	**0.1 Hz**
Beam diameter	150 mm	**280 mm**
Pulse Energy	8 J	**30 J**
Pulse Duration	30-40 fs	**30-40 fs**
Peak Power	0.2 PW	**1.4PW**
Nanosecond Contrast	$\sim 10^{11\text{-}12}$	$\sim 10^{12}$
Focusing	f/2.1	**f/1.3**
Peak Irradiance	2×10^{21} W/cm^2	$\sim 10^{22}$ W/cm^2

H. Kiriyama, et al., Opt. Lett., 43: 2595, 2018

100TW class lasers in Asia

SIOM, China
200TW / 1-5Hz (Homemade)

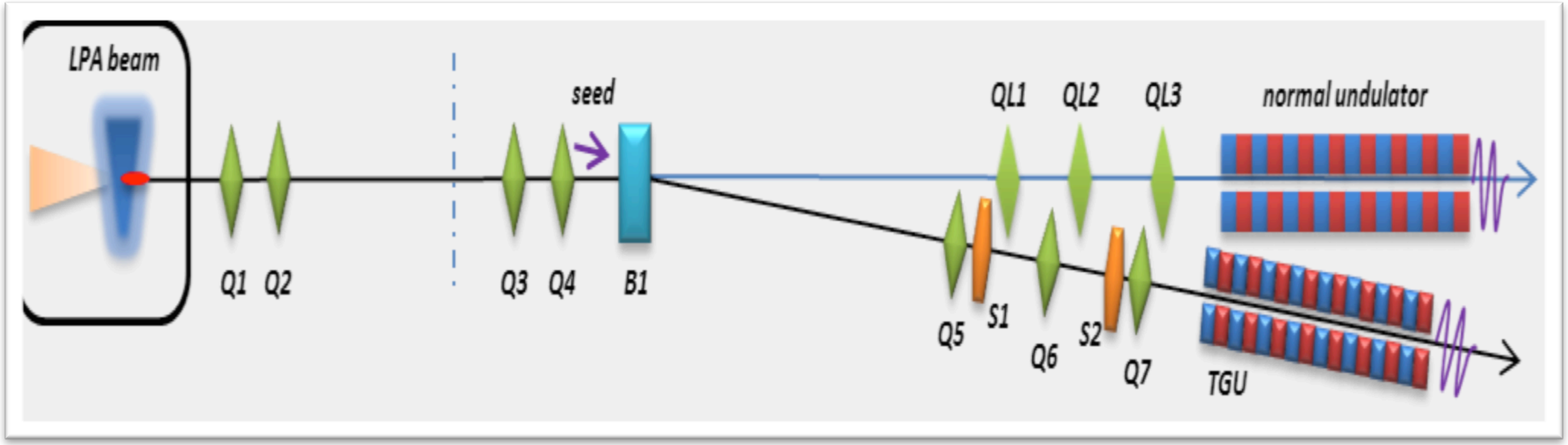
NCU, Taiwan
110TW multi-pulses (Homemade)

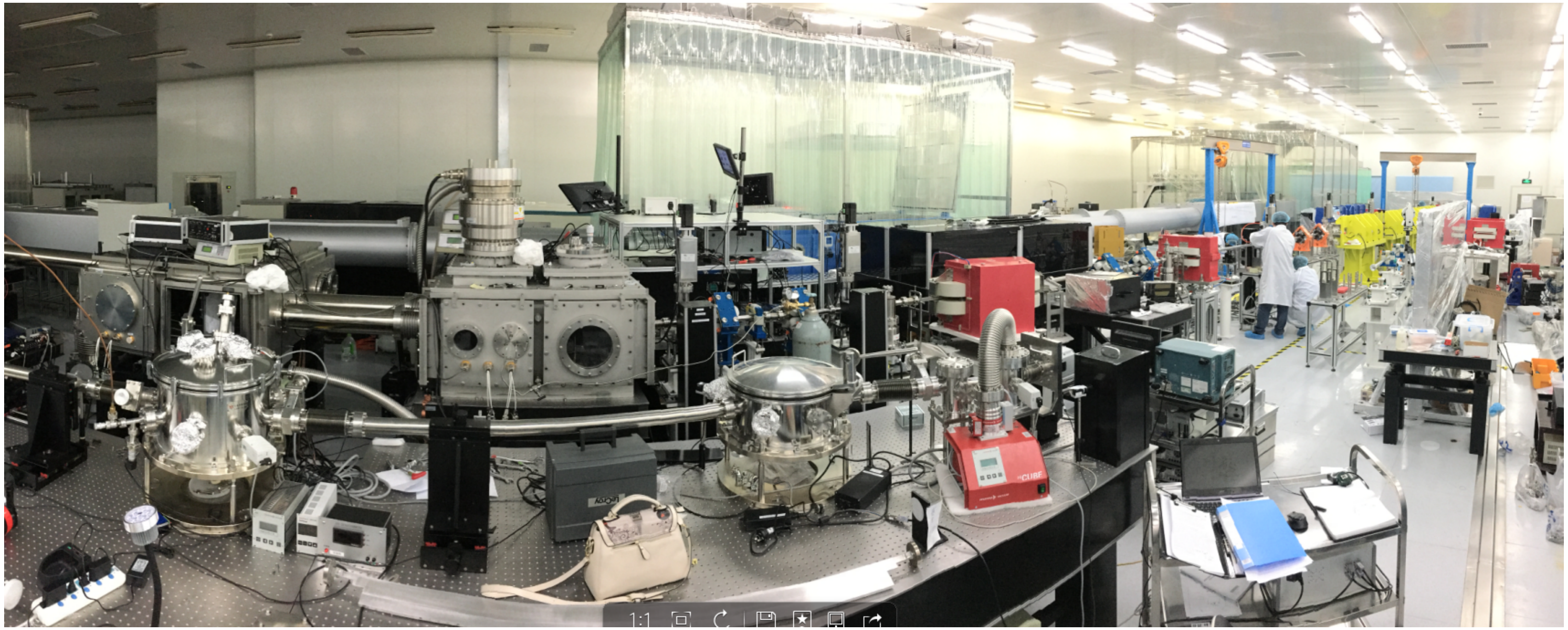
PKU, China
200TW(Thales)

SJTU, China
200TW(AT)

TIFR, India
100TW(AT)

LWFA driven EUV FEL platform



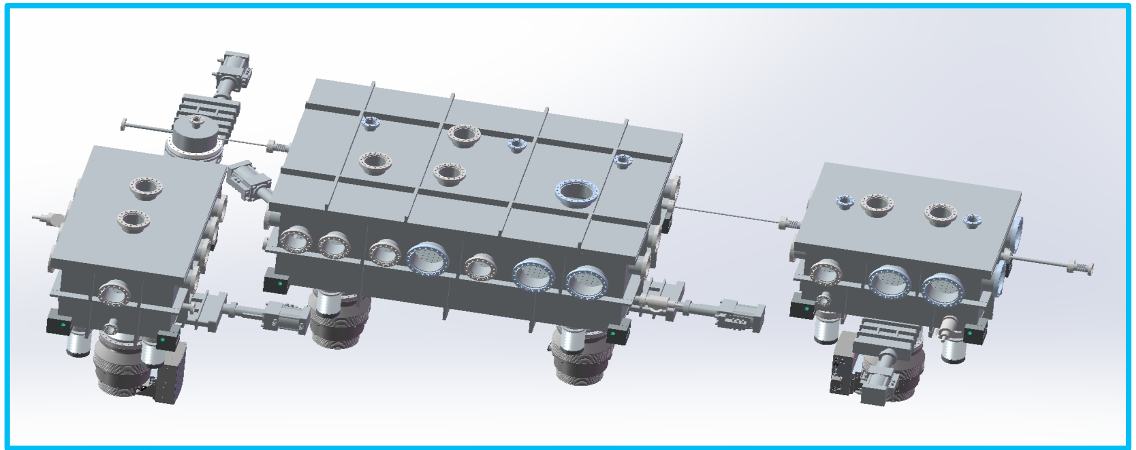


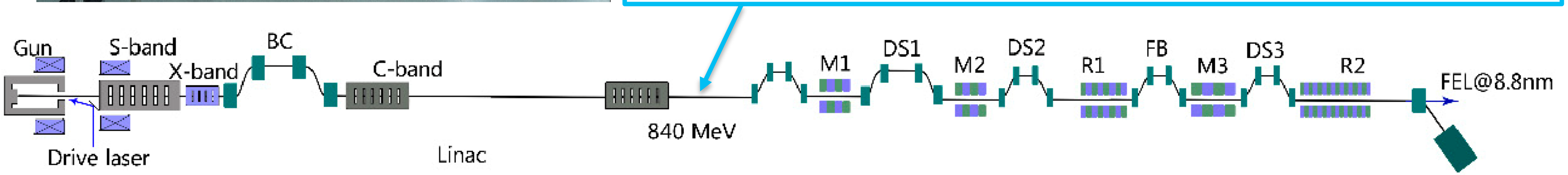
SXFEL based advanced accelerator research platform

Research goal:

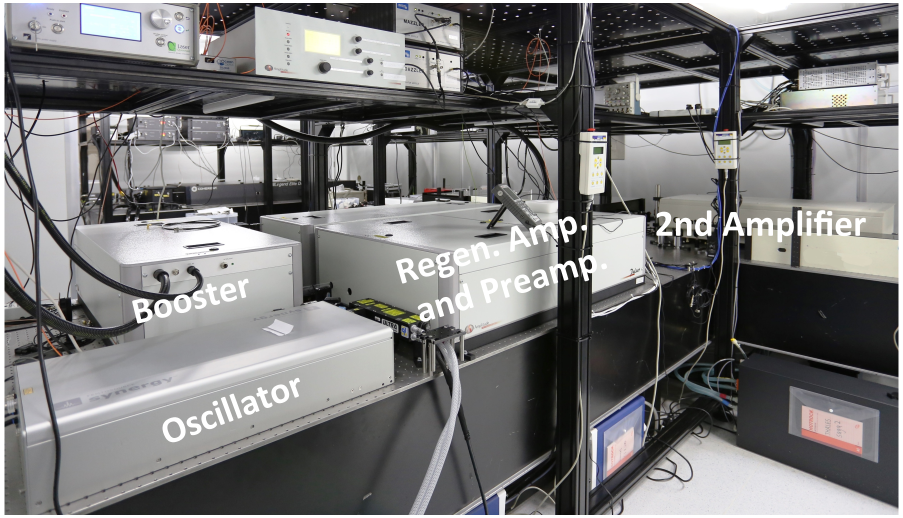
- PWFA based high-brightness beams generation
- High transformer ratio acceleration
- Matched beam transport
- HTR PWFA based Compact FEL

Electron (SXFEL-TF)	
Energy	840MeV
Energy spread(rms)	≤0.1%
Norm. Emittance(rms)	≤1.5mmmrad
Length(FWHM)	≤1ps
Charge	0.5nC
Repetition rate	10Hz

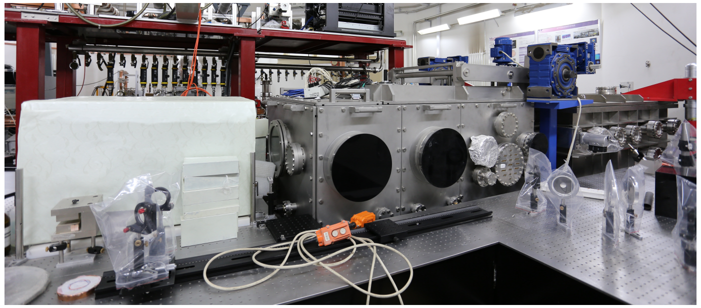


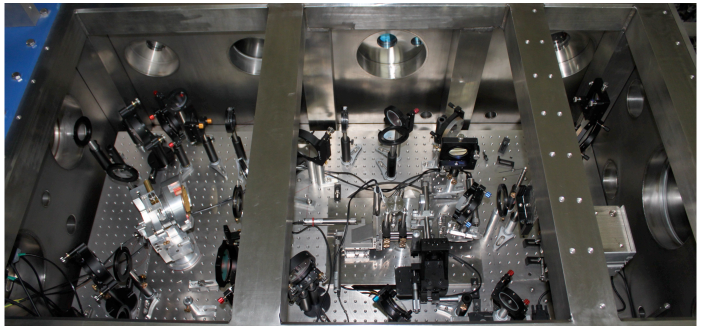


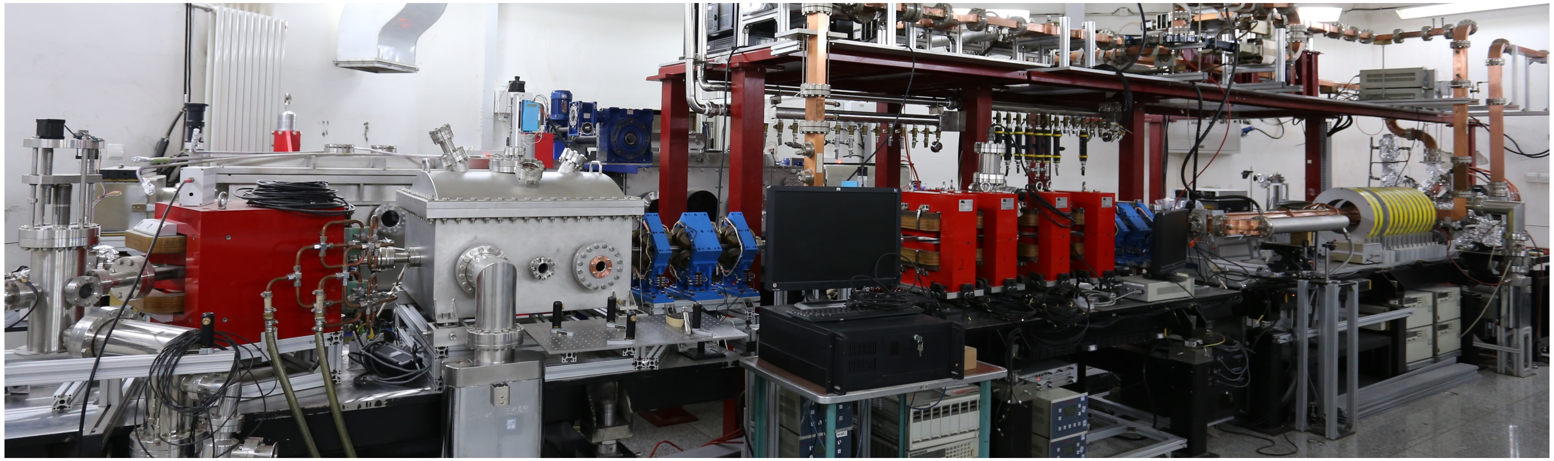
Tsinghua facility for LWFA/PWFA



~30fs ~1J





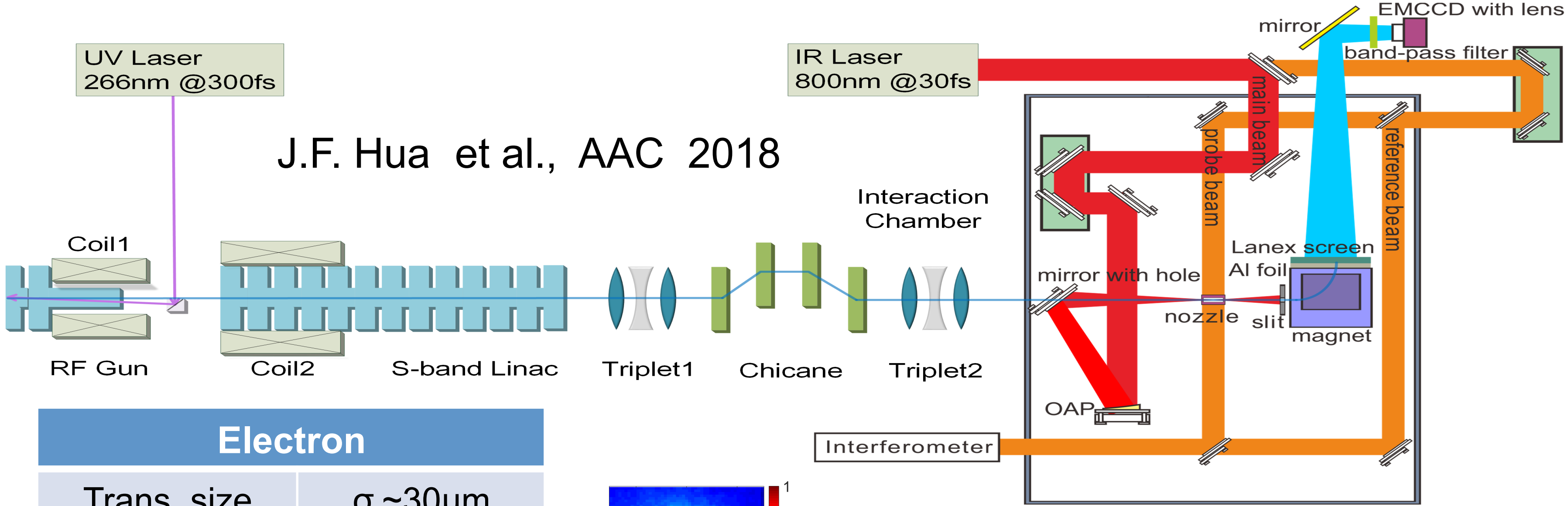


~30TW Laser+45MeV Linac with photo-injector

External injection:
Connecting Linac to LWFA

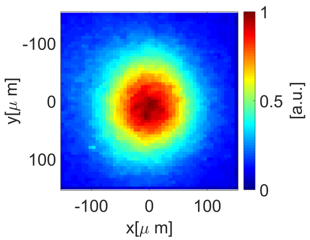
- External Injection from a traditional accelerator (a Linac) into a LWFA is a critical requirement for LWFA's application in HEP.
- Successful demonstration of external injection from Linac to LWFA and the subsequent acceleration with ~100% capture efficiency.

Tsinghua External injection experiment

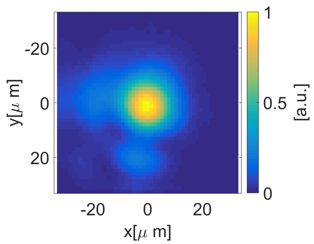


J.F. Hua et al., AAC 2018

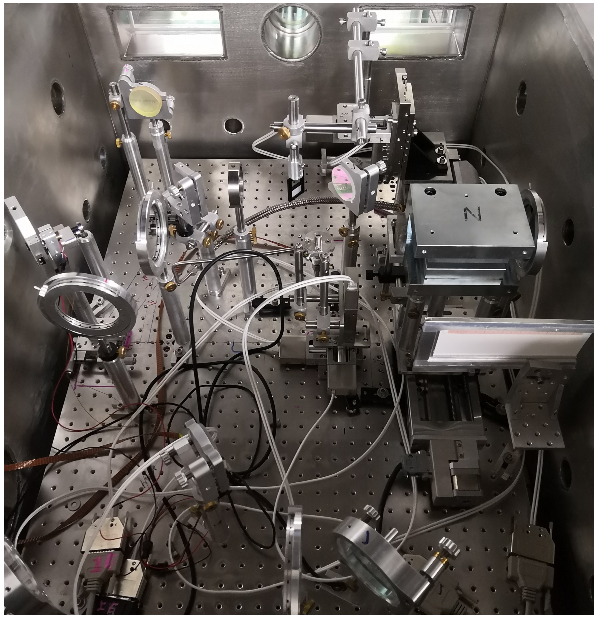
Electron	
Trans. size	σ_r~30μm
Bunch length	σ_z~20fs
Charge	~40fC
Energy	31.3MeV
Plasma	
Density	10^{17} -10^{18} cm^{-3}
Length	6mm
Laser	
Enclosed Power	~5TW
Duration	~42fs
Focus size(FWHM)	~14μm



E. beam profile



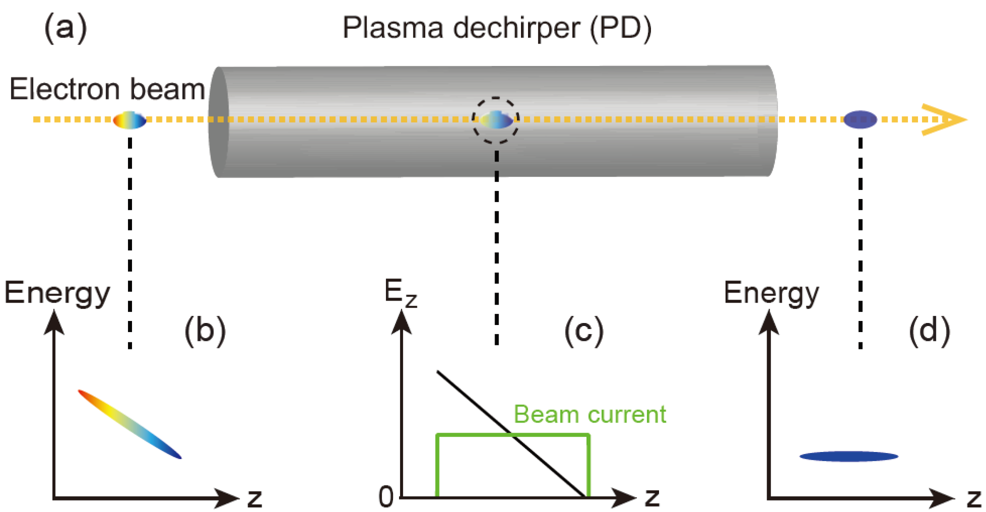
Laser spot



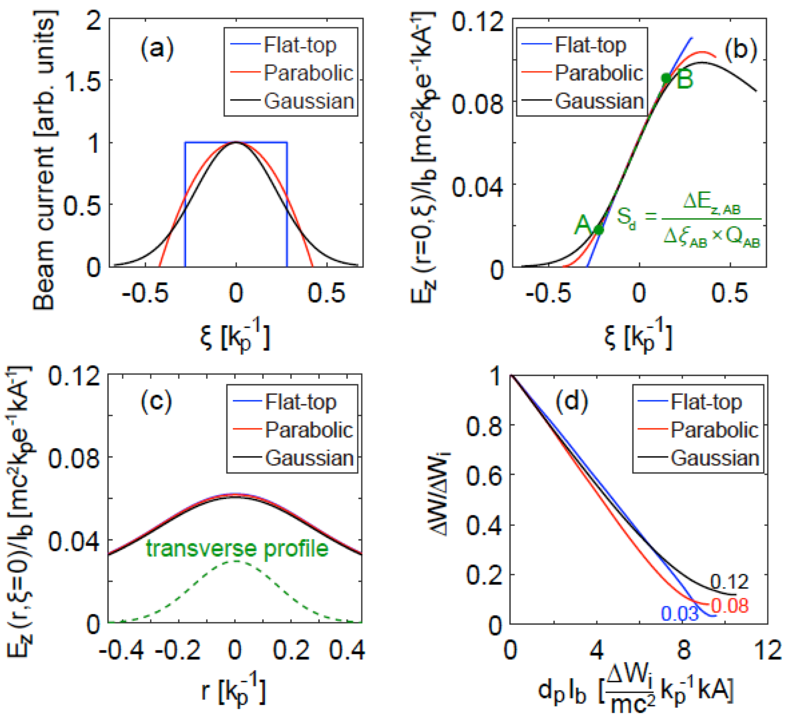
Plasma dechirper for energy spread reduction

- In PBA, slice energy spreads are mainly determined by injection methods, typically at MeV level or even lower
- Relatively large acceleration phase span in PBA leads to large energy chirp (approximately linear)

Energy spread reduction → Energy chirp reduction



Y. P. Wu IPAC 2017



Plasma dechirper for energy spread reduction

A PRELIMINARY EXPERIMENTAL STUDY OF ENERGY CHIRP REDUCTION BY A PLASMA DECHIRPER*

Y. Wu, Y. Du, J. Zhang, Z. Zhou, Z. Cheng, S. Zhou,
J. Hua, C. Pai, W. Lu†
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Abstract

The preliminary experimental study is presented using a low density plasma dechirper to reduce a correlated energy chirp from the 41.5–MeV beam at the linac in Tsinghua University. The plasma dechirper operates through the interaction of the electron bunch with its self-wake to dechirp itself, leading to a reduction in energy spread. The experimental results demonstrate that the projected FWHM energy spread of the beam can be reduced from 0.5 MeV to 0.4 MeV with a 12 mm long plasma dechirper, which are in good agreement with full three-dimensional particle-in-cell simulations.

EXPERIMENTAL SYSTEM

The experiment was performed at Tsinghua Thomson Scattering X-ray source (TTX) which combines an ultra-fast TW Ti:sapphire laser system with a synchronized 45 MeV high brightness RF photogun based linac [10–12]. The experimental system is shown in Fig. 1, which consists of three major components: the TW laser system, the 45 MeV high brightness linac and a high vacuum interaction chamber.

The experiment has two key factors: a stable electron beam with a positive energy chirp and a controllable low-density plasma source as the dechirper. To produce the stable

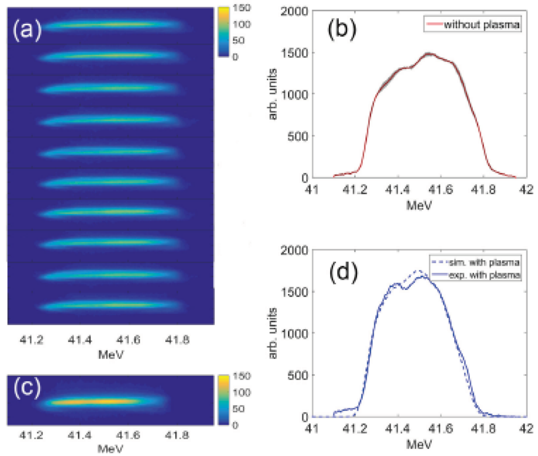
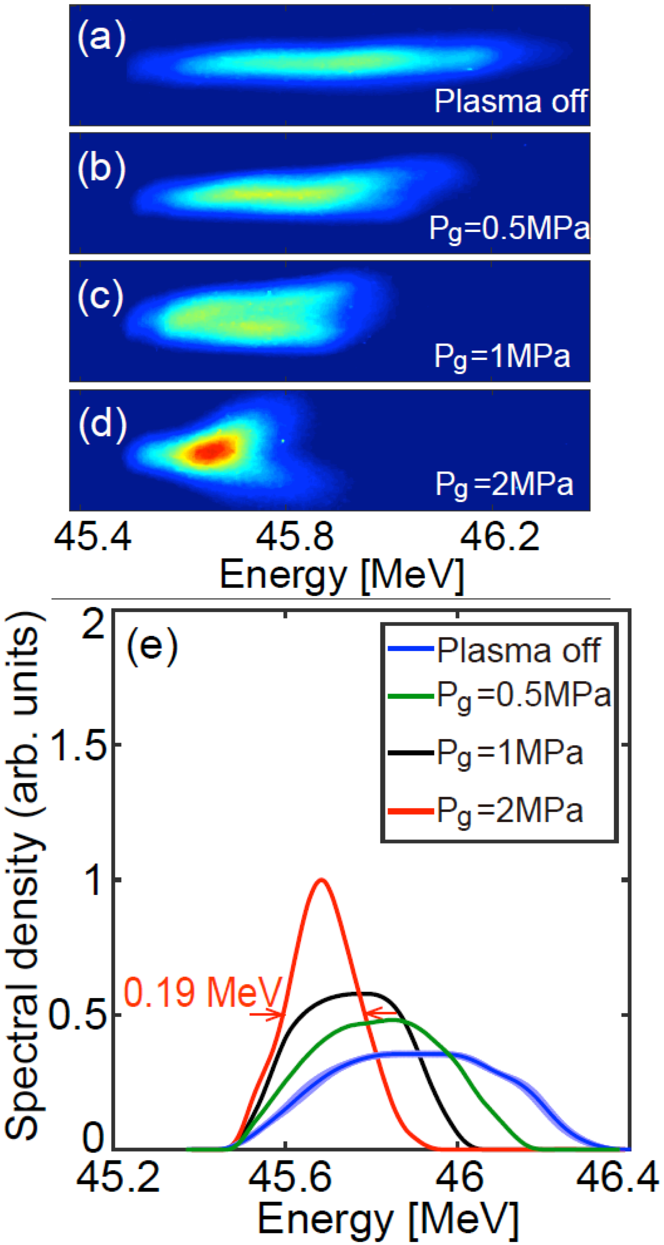
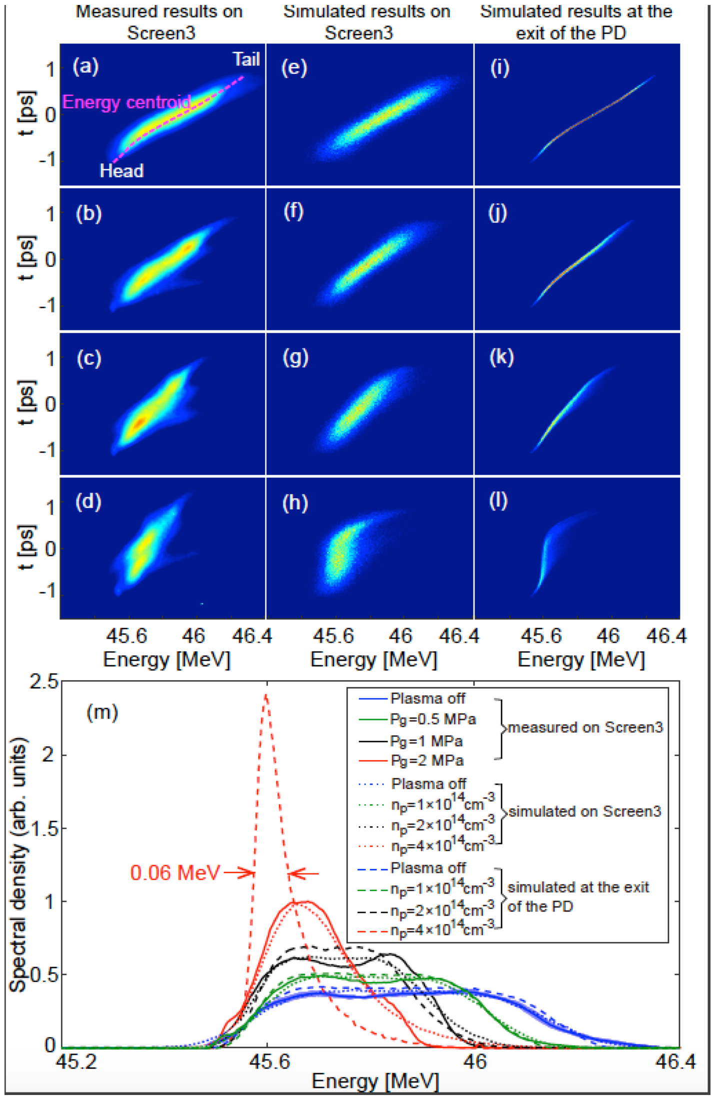


Figure 5: The typical energy profiles (10 shots) of the electron beam observed in the energy spectrometer without laser produced plasma. (b) The energy spectra for the plasma-off shots. (c) One beam energy profile sample of plasma-on shot. (d) The energy spectra for this plasma-on shot case. The solid line shows the experimental result and the dashed line shows the simulation result.

Demonstration of a plasma dechirper
With energy spread down to 0.13%



Beam longitudinal phase space evolution

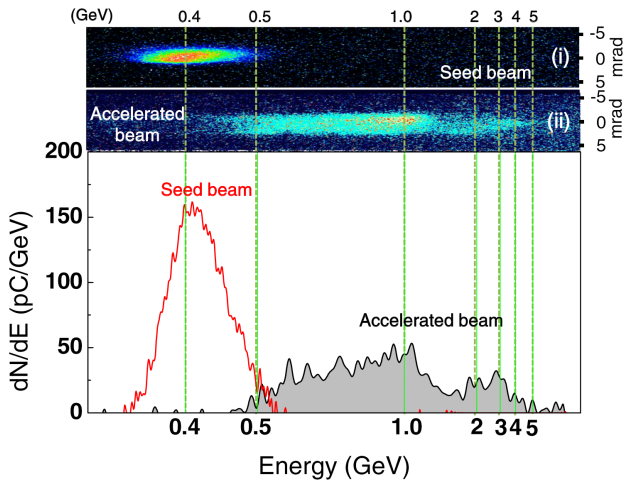


AAC 2018 oral

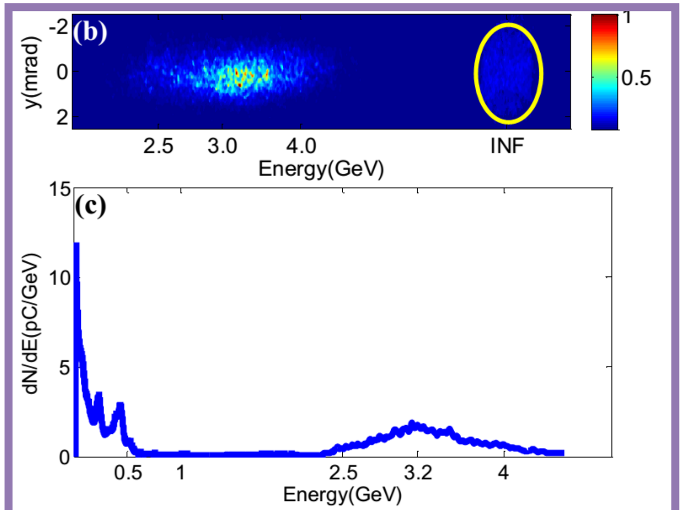
LWFA: Energy gain

Institute for Basic Science

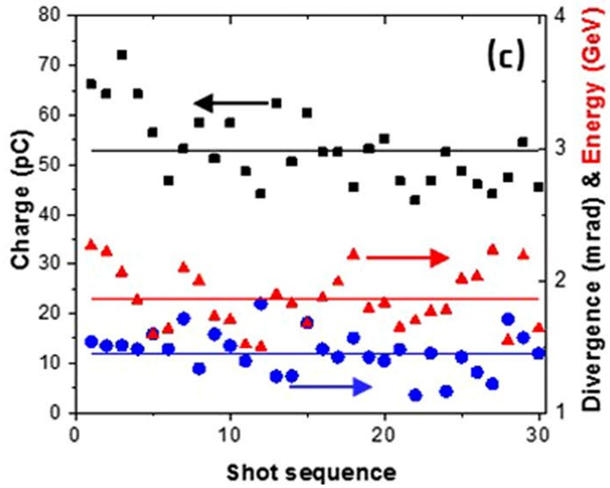
Broad energy spread



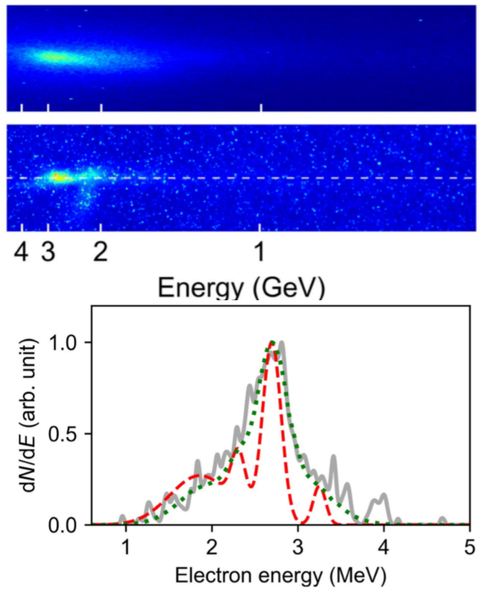
H. T. Kim, PRL, 111:165002, 2013



Better control of spectrum and stability



H. T. Kim. Sci, Rep., 7: 10203, 2017



J. Shin, PPCF, 60:064007, 2018

A cascaded LWFA using an capillary discharge waveguide powered by a 300-TW laser pulse

SIOM

LWFA: Energy spread

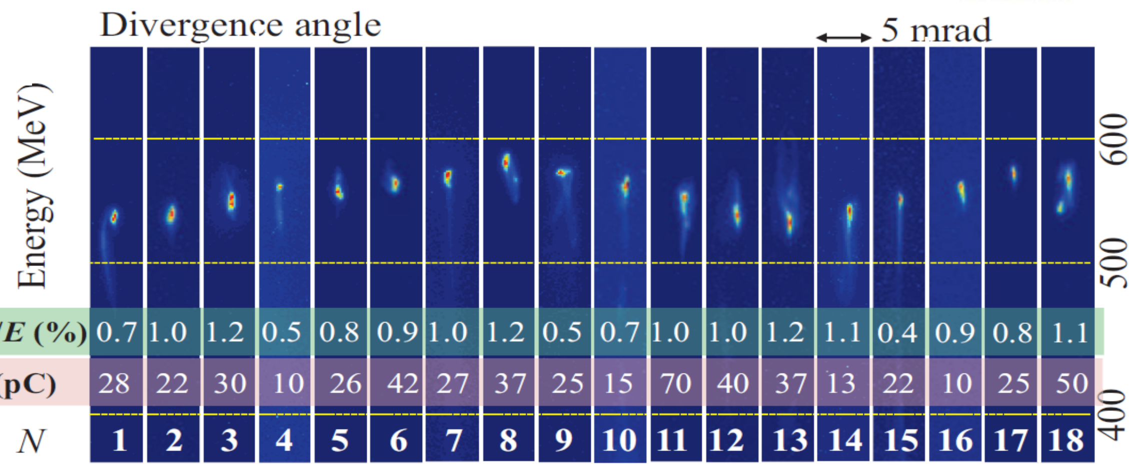
Brightness: ~6.5×10^{15} A/m^2/0.1%

Energy spread: 0.4-1.2%

Charge: 10-80 pC

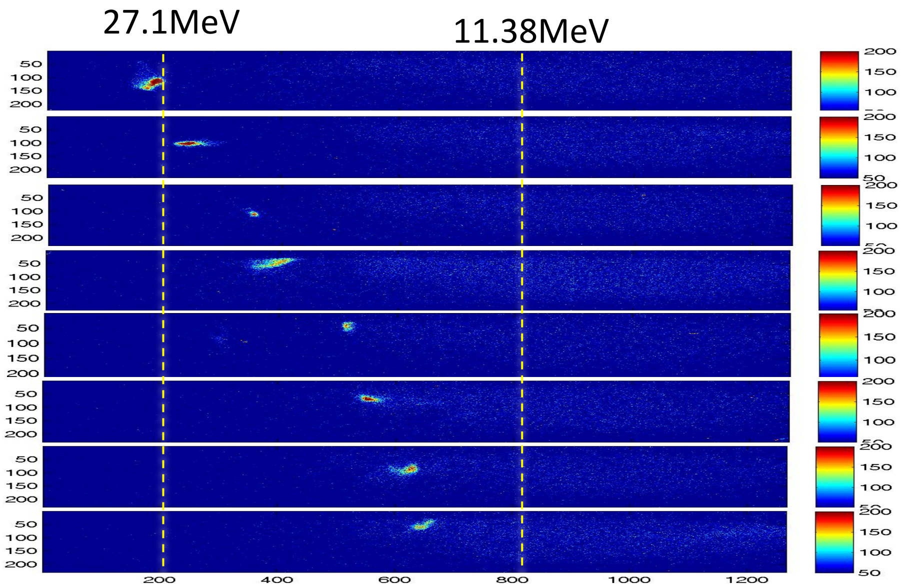
Divergence： ~0.2 mrad

Energy gain: 200~600 MeV



N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
ΔE/E (%)	0.7	1.0	1.2	0.5	0.8	0.9	1.0	1.2	0.5	0.7	1.0	1.0	1.2	1.1	0.4	0.9	0.8	1.1
Q (pC)	28	22	30	10	26	42	27	37	25	15	70	40	37	13	22	10	25	50

W. Wang et al., PRL 117,124801(2016)

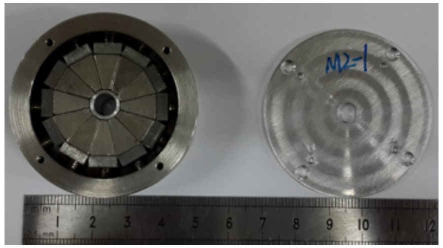


- With AES below 0.5MeV (rms), the lowest 0.18MeV
- With RES around 1-2% (rms), the lowest 0.8%

To be submitted

LWFA: Emittance measurement

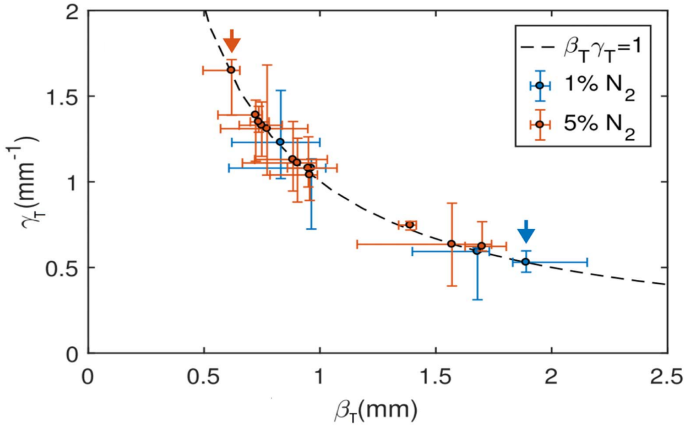
- Systematical studies of the single shot emittance measurement method using PMQ (***R. Weingartner et al., PRSTAB 2012***) with various non-ideal factors

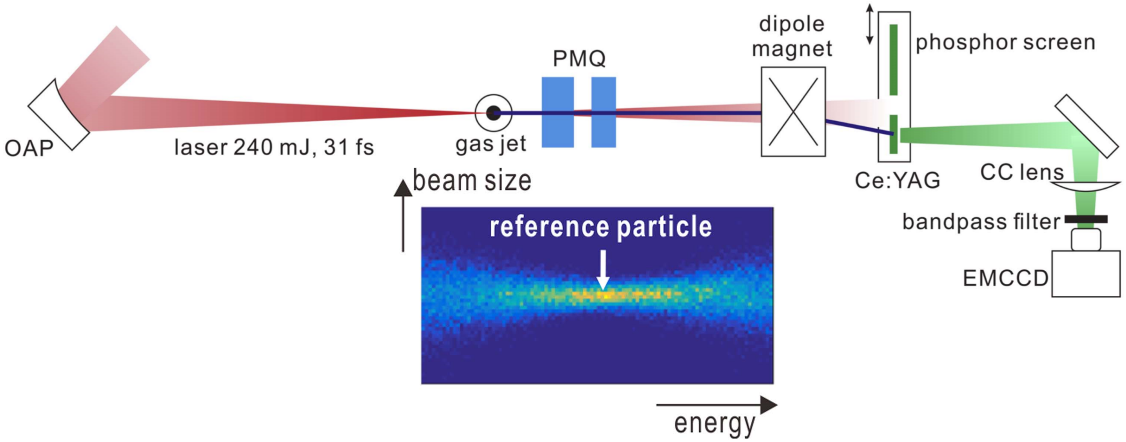


  - ✓ Aberration of high order field / The transverse position misalignment and angular fluctuation /Angular misalignment
- The method's capability for sub-100 nm rad emittance measurement has been confirmed

F. Li, et al., PPCF, 60: 014029, 2018

Twiss parameters measurement using PMQ





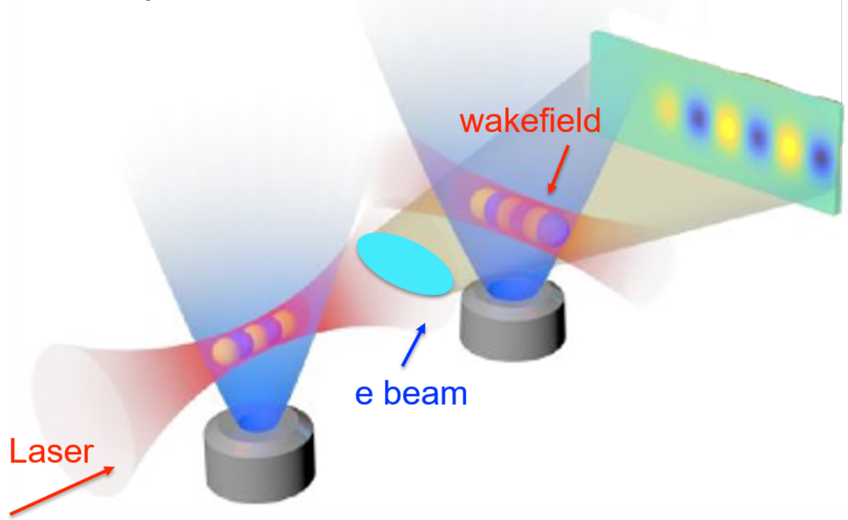
Matched beams with α_T~0

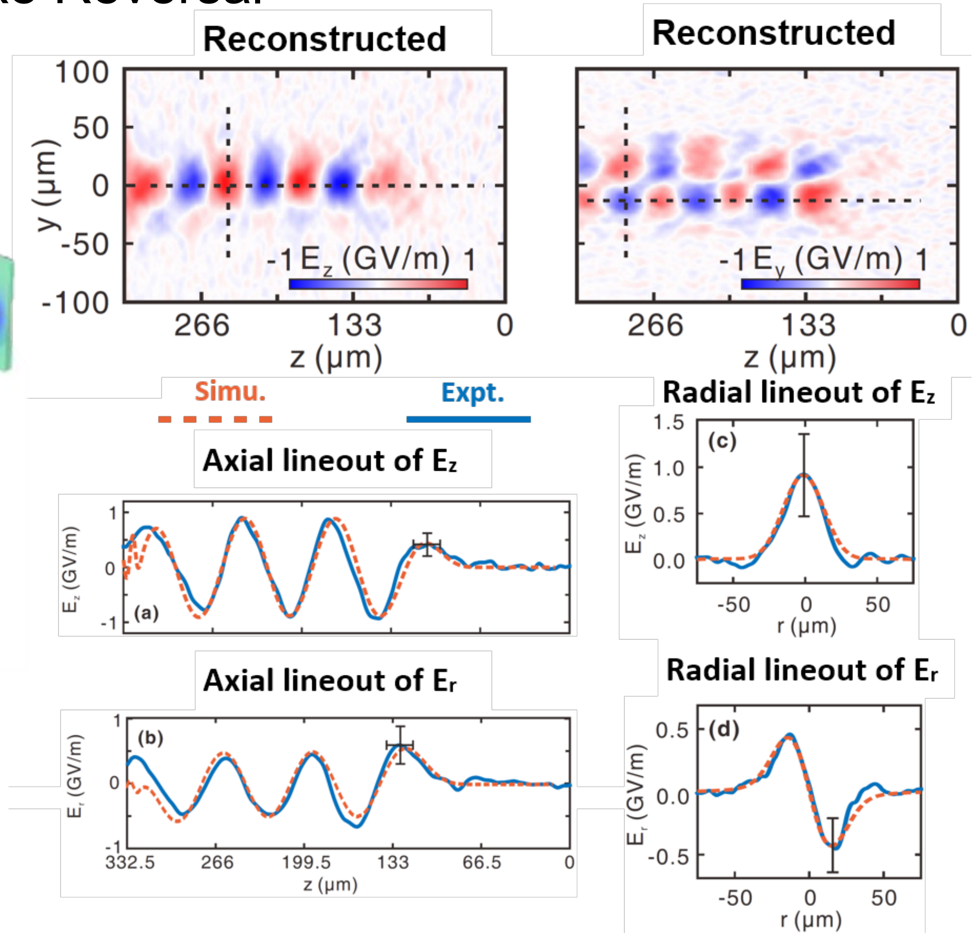
F. Li, et al., PPCF, 60: 044007, 2018

LWFA: Wakefield snapshot

- First measurement of the field structures in a plasma wake!
- Observation of the Plasma Wake Reversal

Conceptual illustration of FREP:





Challenges:

- ✓ Microscopic scale
- ✓ Light speed moving
- ✓ Transient lifetime(ps)
- ✓ Intense field

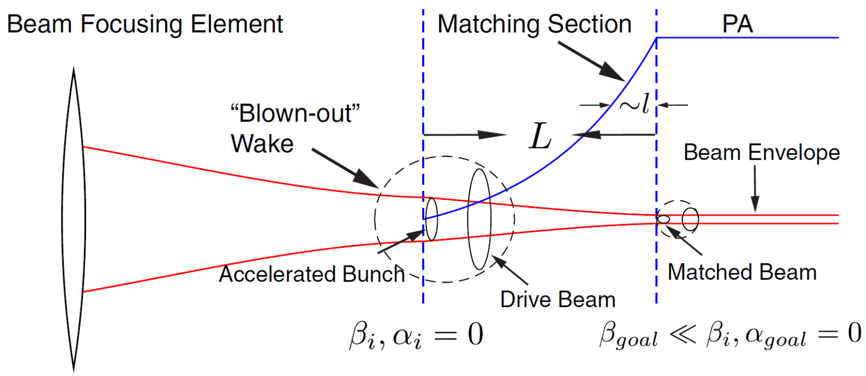
C. J. Zhang, et al. PRL, 119:064801, 2017

Staging Schemes:

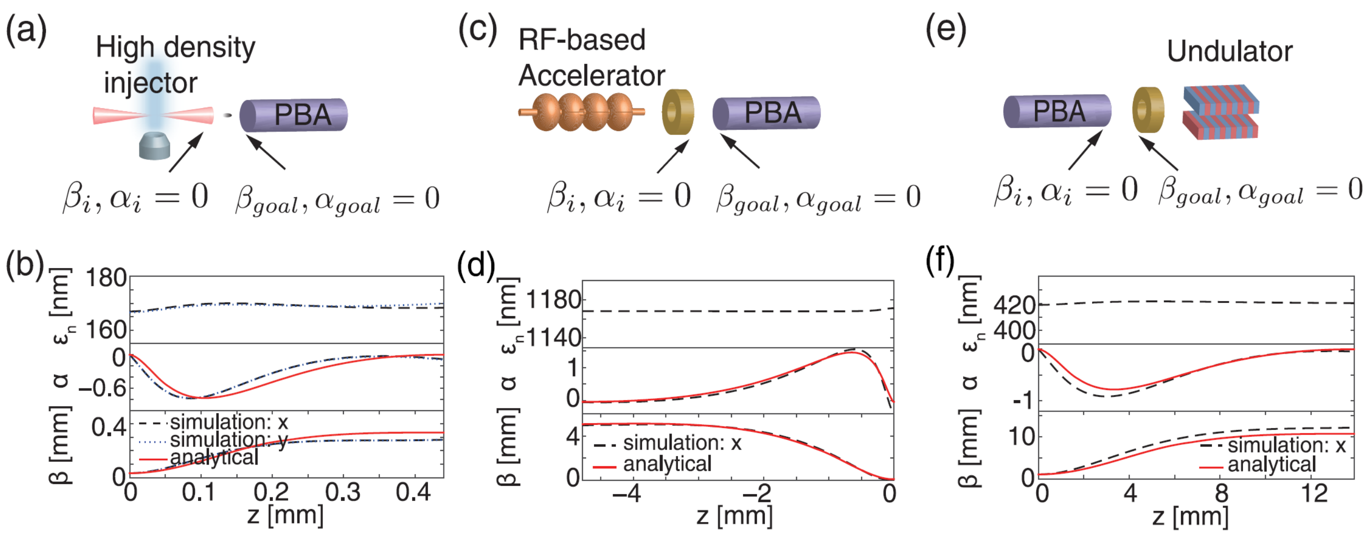
Phase space matching based on longitudinal plasma structure

- Combining a longitudinal tailored plasma structure with the linear focusing force in the nonlinear blowout wake

- Phase space matching between sections with negligible emittance growth



- Working for different scenarios

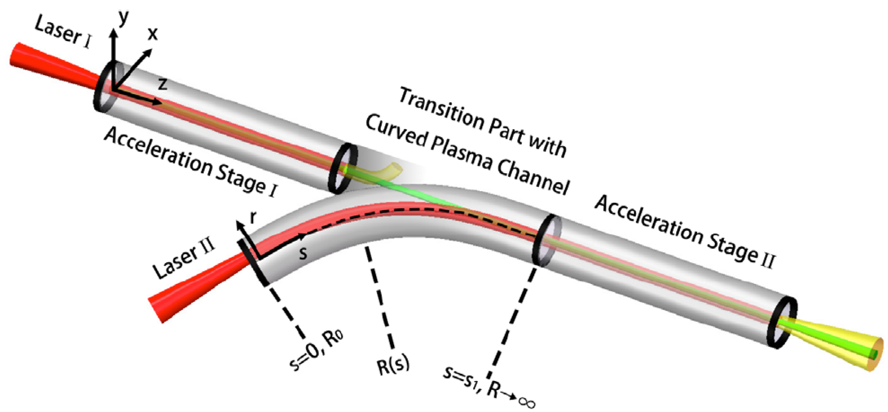


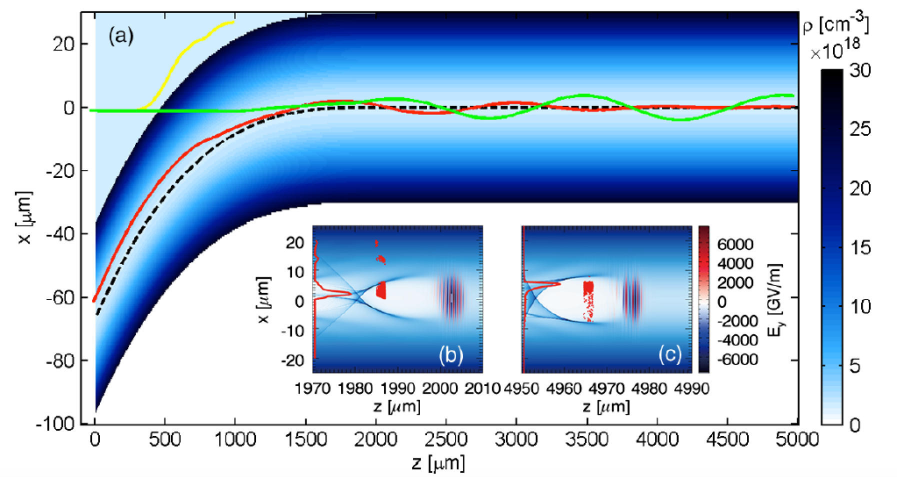
X. L. Xu, et al., PRL, 116: 124801, 2016

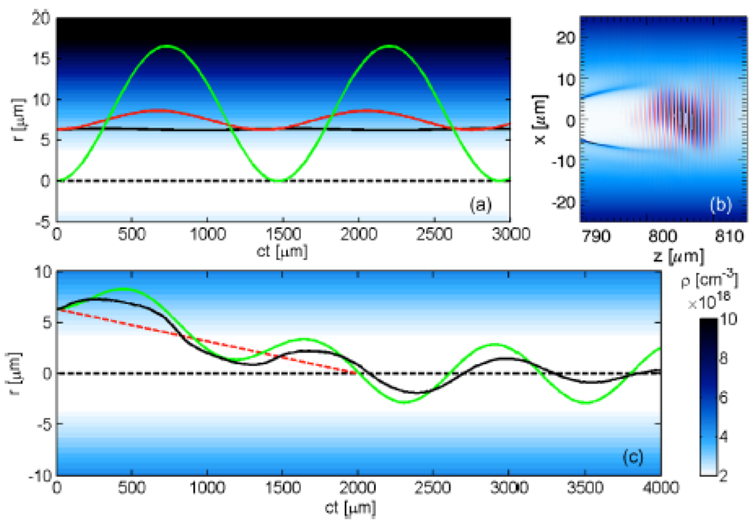
Staging Schemes:

Multistage coupling of LWFA with curved plasma channels

- A curved plasma channel is proposed to guide the laser in the second stage of LWFA
- Electron beam from the first stage can directly propagate into the second stage
- Good coupling between two stages can be achieved with proper design







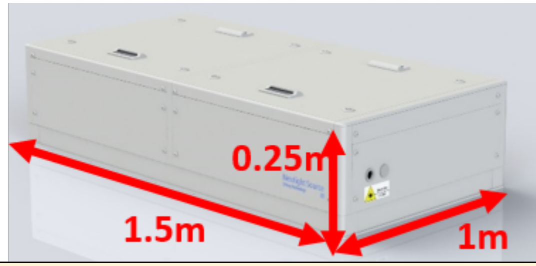
J. Luo, et al., Phys. Rev. Lett. 120 : 154801, 2018

Robust compact laser development for application in China

A joint effort of Tsinghua, NCU and Qifeng New Light Source Co., China

The Goal

- Building turn-key lasers for real application: a laser built by the user and for the user
- Laser systems with much improved long term operation performance and much reduced size (by factor of 3-4)
- A compact 200TW system under production

20-40TW Turn-key level Ti:Sapphire laser	
Company/Model	Qi-NLS Iteration-L
Product	
Size	1.5mx(1-1.3m)x0.25m
Energy stability（RMS）	<0.7%
Contrast	$>5x10^{10}$
Duration	<30fs
Power	20-40TW

A Possible Middle Step for AAC towards Colliders

Plasma Based Injector for 100km CEPC

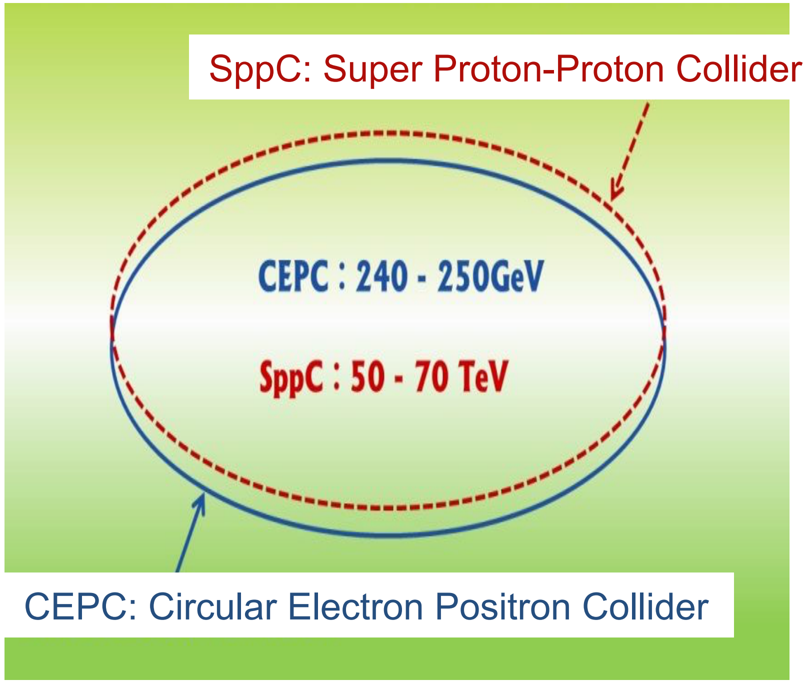
- CEPC (**Circular Electron Positron Collider**) is a major high energy physics plan under strong promotion in China to build a 100km circular machine for a Higgs Factory.

- A high energy injector (40GeV level) is needed to inject e+/e- beams into the main ring.

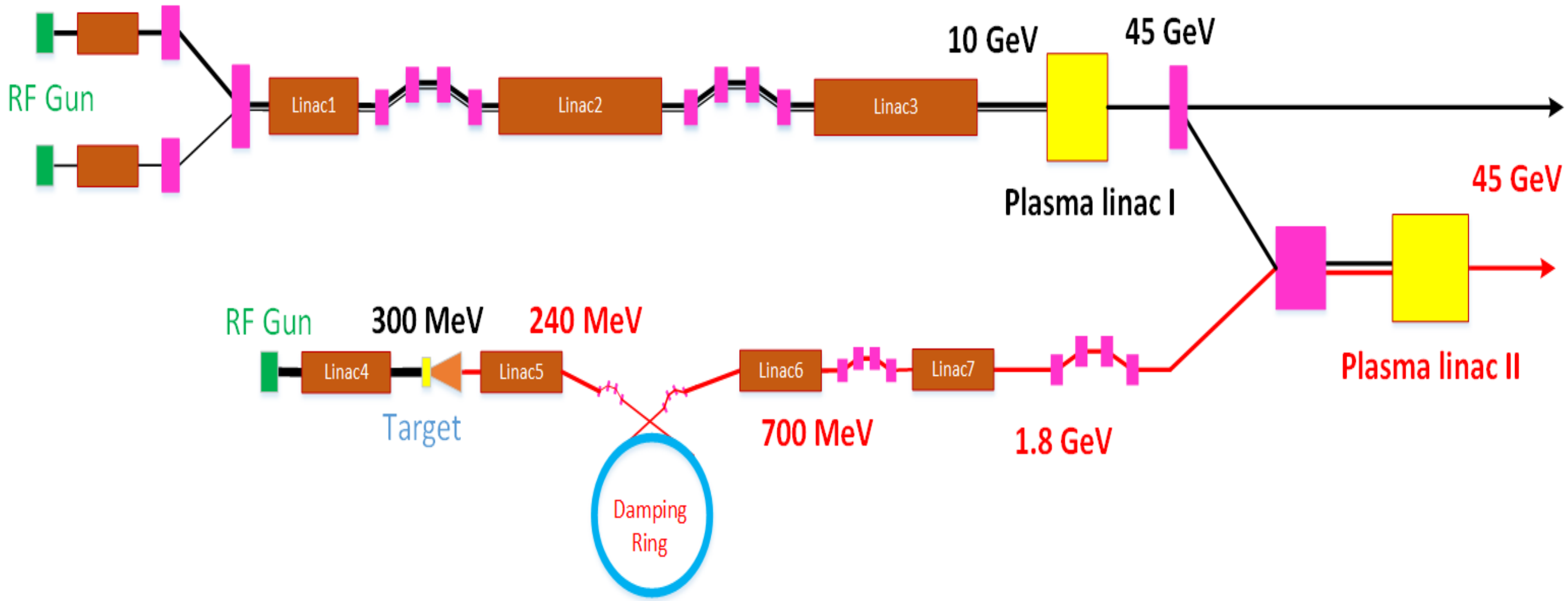
- Plasma based schemes (PWFA) may provide a novel and cost effective solution for this injector.

- A joint research group of Tsinghua Univ. and IHEP has been formed since 2017 to study the feasibility of using plasma based acceleration as a novel solution for CEPC injector.

Circular Higgs Factory (Phase I)
+SppC (Phase II) at same tunnel



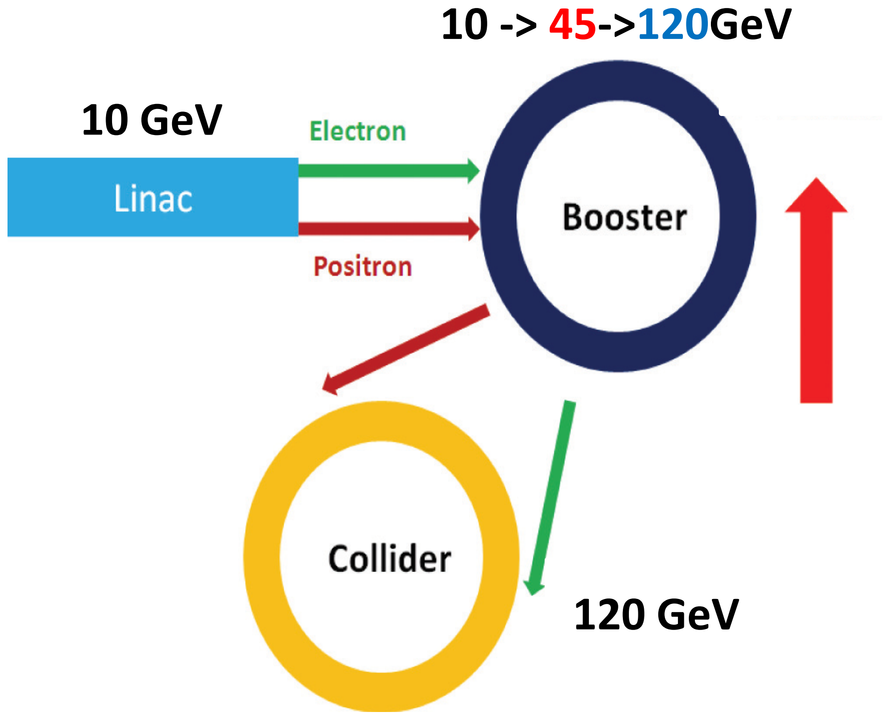
A preliminary design of CEPC plasma based high energy injector



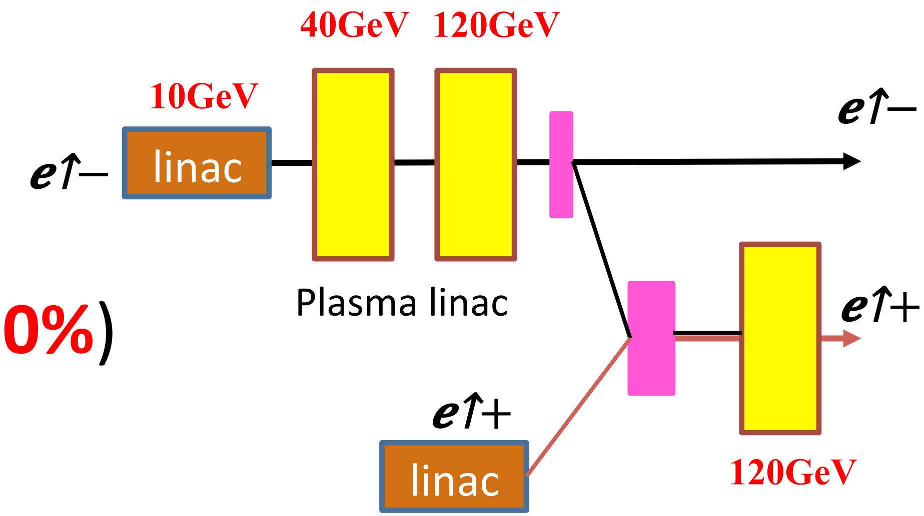
- Driver/trailer beam generation through Photo-injector
- HTR PWFA with good stability (single stage TR=3-4, Cascaded stage 6-12, high efficiency)
- Positron generation and acceleration in an electron beam driven PWFA using hollow plasma channel (TR=1)

Ref: CEPC CDR

- **Single stage HTR PWFA**
  - 45GeV
  - TR=3~3.5
  - Energy Efficiency (**60%/30%**)



- **Cascaded HTR PWFA**
  - 120GeV
  - TR=3 (total TR=12)
  - Energy Efficiency (**40%/20%**)

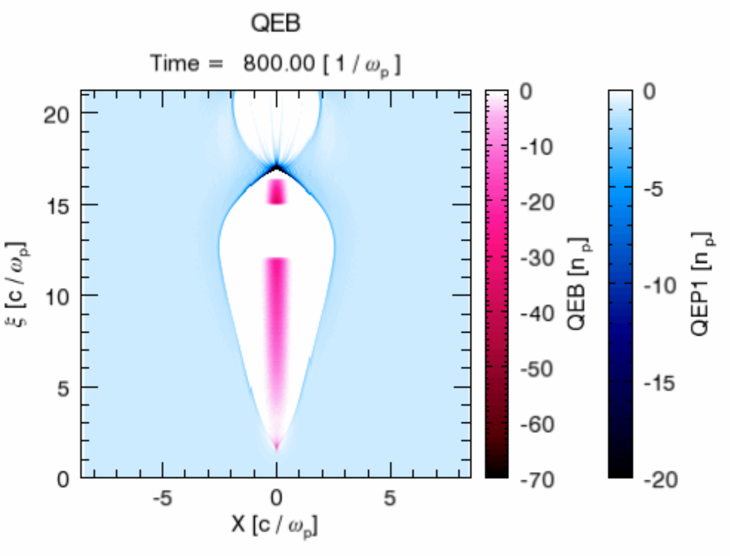


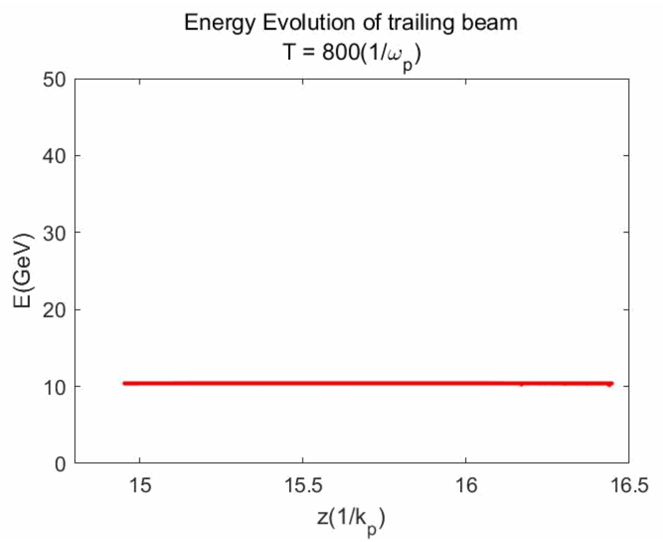
Beam requirements

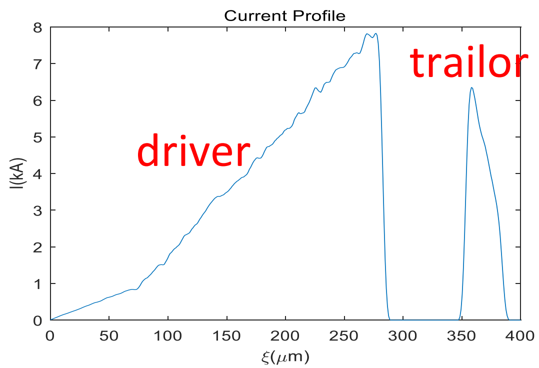
- Beam average power (kW 100Hz)
- Beam charge per-bunch (~nC)
- Beam energy spread (<0.2%)
- Beam geometric emittance (<0.3mm mrad)

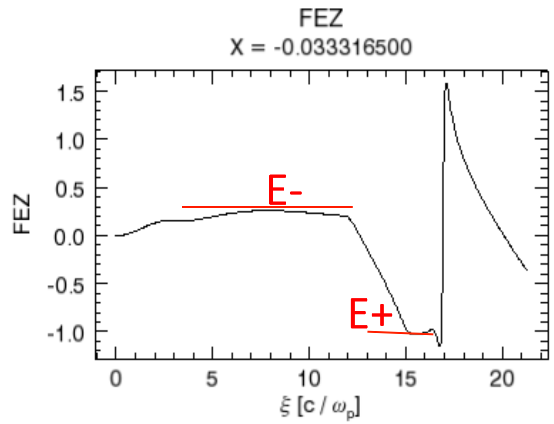
Electron Acceleration

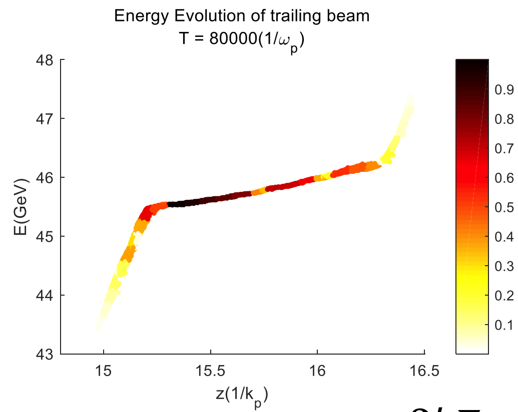
HTR PWFA + Energy Dechirper







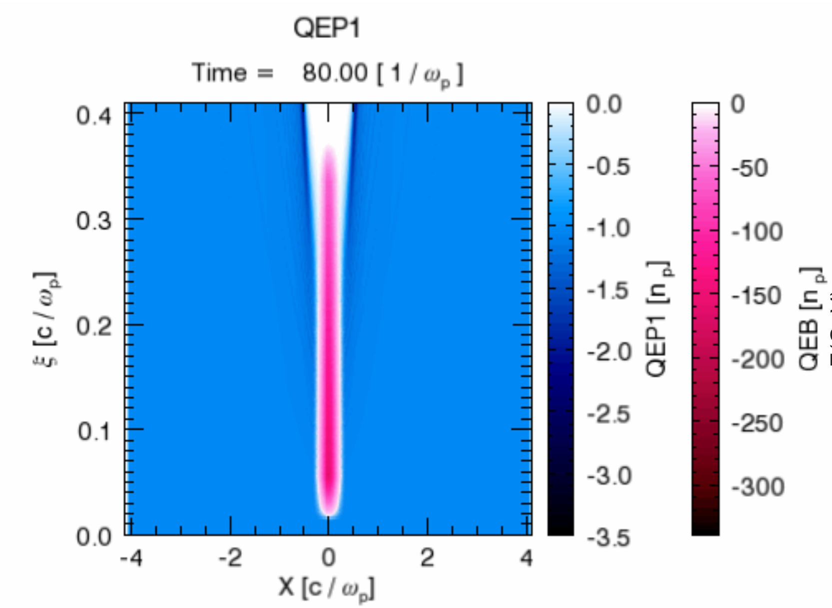


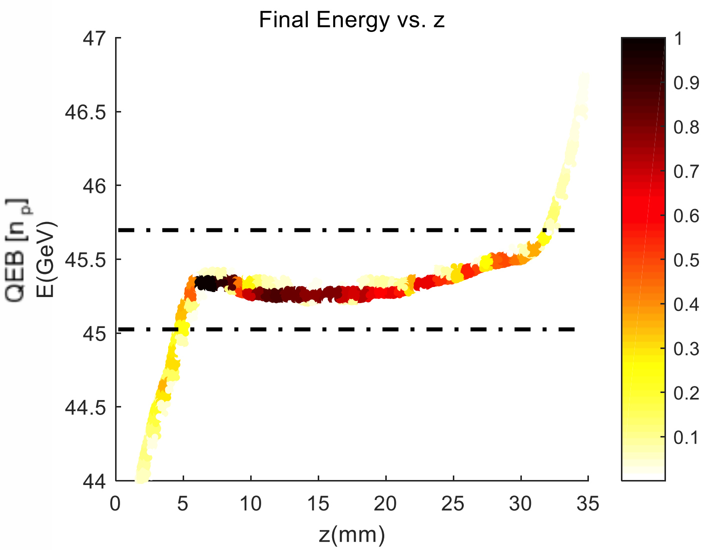


$\delta{\downarrow}E = 0.62\%$

Electron Acceleration

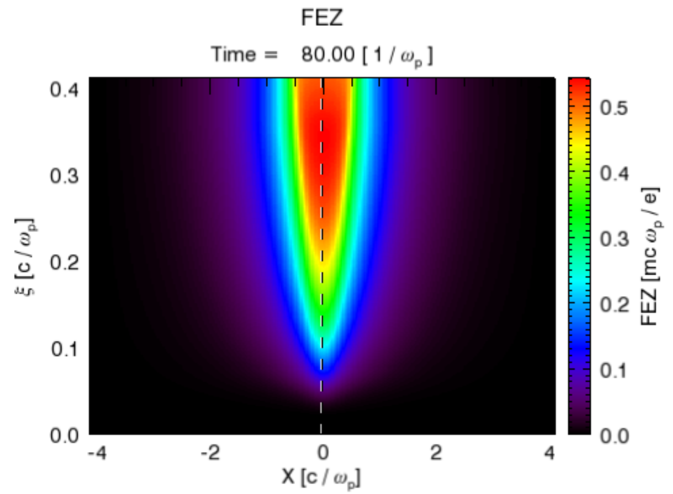
HTR PWFA + Energy Dechirper

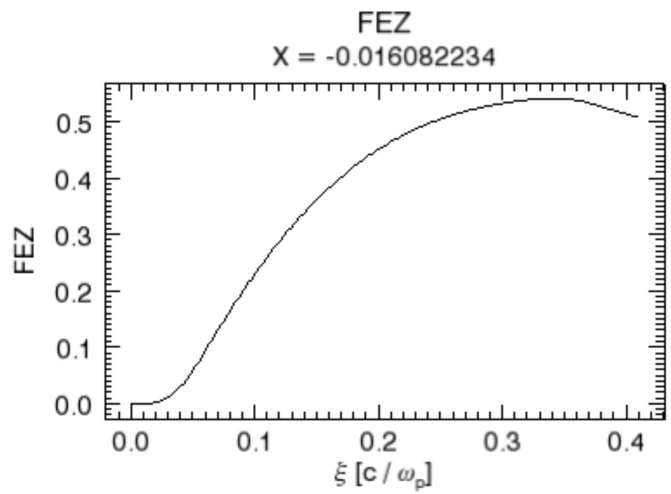




$\delta_E = 0.20\%$

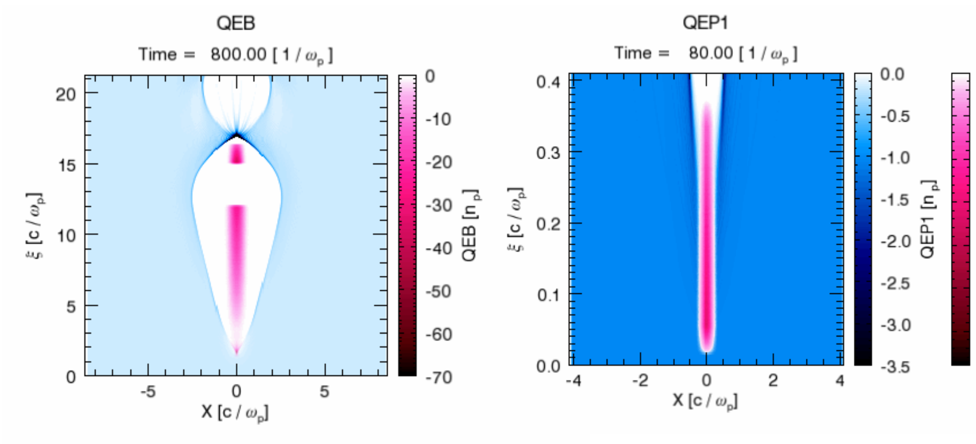
$ratio = 86.39\%$





Electron Acceleration

HTR PWFA + Energy Dechirper



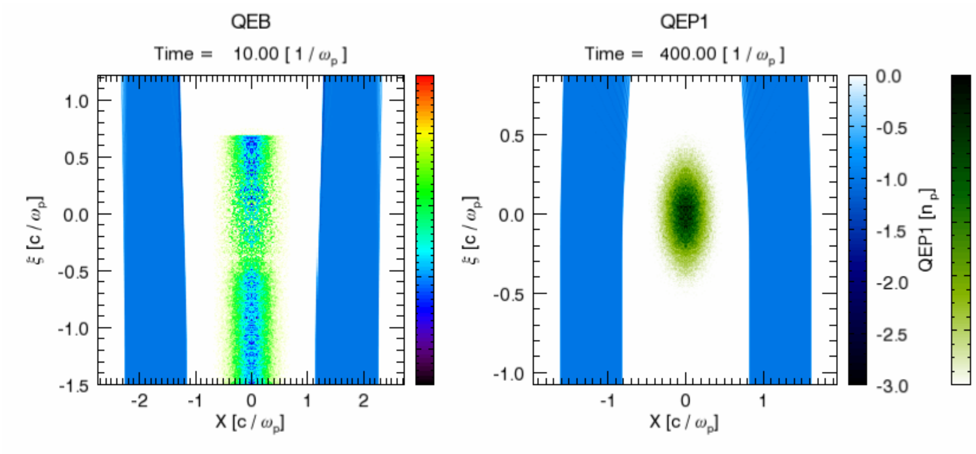
Input parameters	
Plasma density acc(cm-3)	5.15*10^16
Plasma density de (cm-3)	3*10^15
Driver charge nC	5.18
Driver energy GeV	10
Trailor charge nC	1.0
Trailor energy GeV	10

Output parameters	Acceleration
Trailor energy (GeV)	45.5
Trailor normalized emittance (nm rad)	1.1
TR	3.55
Energy spread (%)	0.7
Efficiency (driver -> trailor)	68.6%
Plasma length (m)	1.87

Output parameters	Dechirper
Trailor energy (GeV)	45.3
Trailor normalized emittance (nm rad)	1.89
Energy spread %	0.2
Overall Efficiency	59.4%
Plasma length (m)	0.23

Positron Acceleration

Beam Combine+ Energy Dechirper



Input parameters	
Plasma density acc(cm-3)	1.77*10^16
Plasma density de (cm-3)	9.1*10^15
Driver charge nC	2.1
Driver energy GeV	45
Trailor charge nC	1.0

Output parameters	Acceleration
Trailor energy (GeV)	45.3
Trailor normalized emittance (nm rad)	1.1
TR	1
Energy spread (%)	0.29
Efficiency (driver -> trailor)	46.82%
Plasma length (m)	22

Output parameters	Dechirper
Trailor energy (GeV)	45.2
Trailor normalized emittance (nm rad)	1.0
Energy spread %	0.14
Overall Efficiency	45.4%
Plasma length (m)	1.47

Key Technology Base

Driver and Acceleration Media

- Shaped Bunch Generation
- Plasma source (1-10m)
- Hollow plasma channel generation

Accelerator and Beam Manipulation

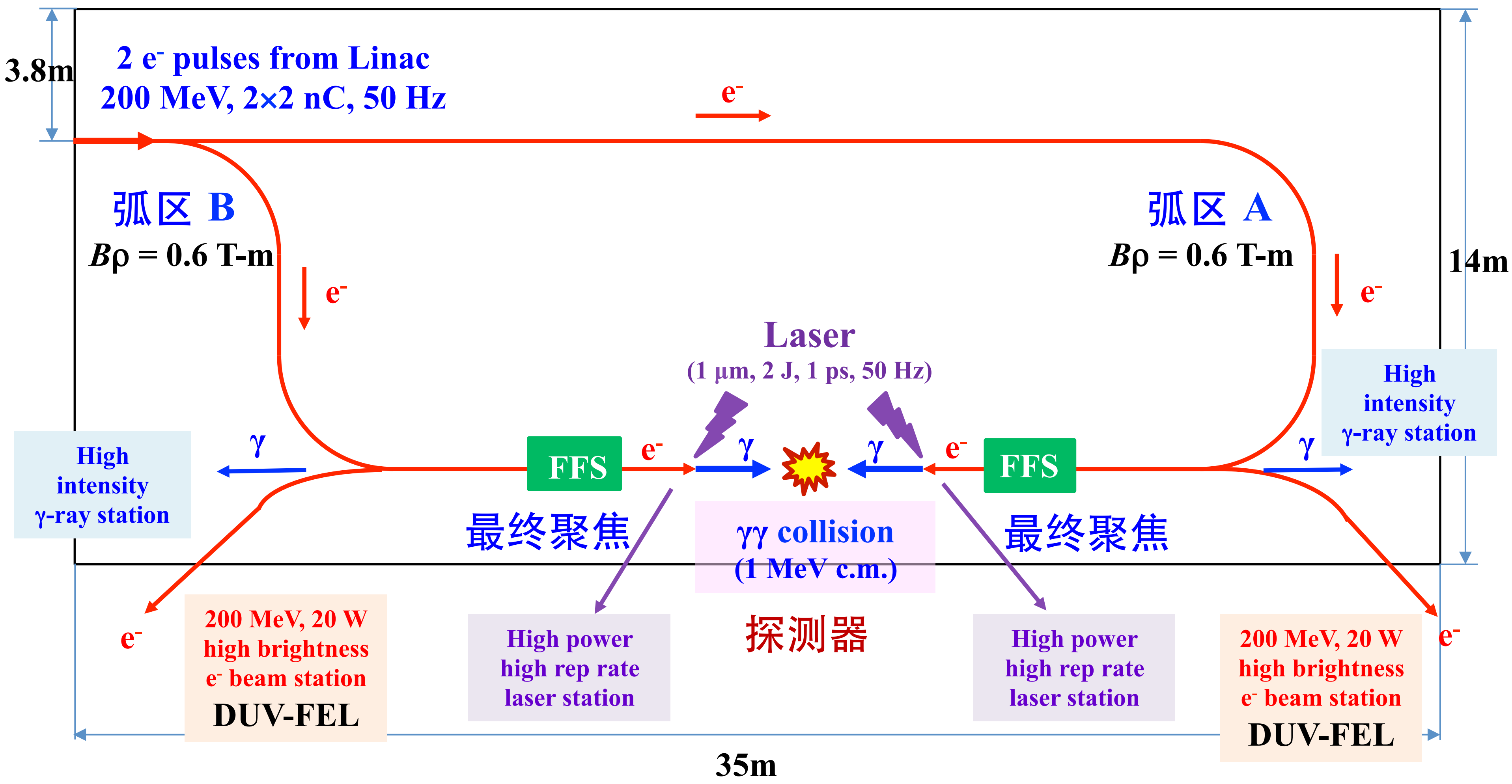
- HTR PWFA
- Positron acceleration
- External injection
- Plasma dechirper

All have been tested by preliminary experiments!

ICFA Mini-Workshop on γγ Collider (Tsinghua)

- ~100 participants from 9 countries
- A joint stage of several scientific communities: HEP (γγ) + NP (γ-ray) + accelerator + laser

A proposed γ−γ collider in China (IHEP)



- Chuang Zhang and Weiren Chou For the BggC Study Group

Main Parameters

电子束		激光		伽马射线	
E	200 MeV	λ	1.054 μm	E(c.m., peak)	**1 MeV** (2 x 0.5)
Charge	**2 nC**	Waist	5 μm	N (total)	**2×10^{11} /s**
σ(x,y)	2 μm	Rayleigh	298 μm	Rep rate	50 Hz
ε	**6.4 nm**	Pulse energy	**2 J**	σ(x,y)	2 μm
β*	626 μm	Pulse length	**1 ps**	*L*	**1×10^{27} $cm^{-2}s^{-1}$**
σ(z)	2 ps	Rep rate	**50 Hz**	∫*L*	10 nb^{-1} /year
Rep rate	50 Hz	Crossing θ	167 mrad	Cross section	3 μb
Crossing θ	0 mrad	d (IP-CP)	313 μm	Event rate	7 /hr
L (geometric)	1.6×10^{28}	Nonlinear a_0	0.45		30,000 /year

Event rate:

- γγ → γγ: L = 1 x 10^{27}, σ = 3 μb ⇒ several events per hour (30,000 events/ year) (*<u>Comparable to the Higgs rate in CEPC,</u> in which the luminosity is higher by 7 orders of magnitude, but cross section is smaller by 7 orders of magnitude*)
- γγ → e^+e^-: L = 1 x 10^{27}, σ = 100 mb ⇒ 100 events per second

Summary

- The AAC community in Asia is growing fast! Many institutes invest heavily into this area

- The quality of the work is getting better and better, and there will be more leading results from Asia in the future

- More work will focus on how to build an accelerator: using the language of accelerator physics, such as phase space, matching, ……

- It is an exciting time for AAC community, Asia as well

Thank you for your attention!