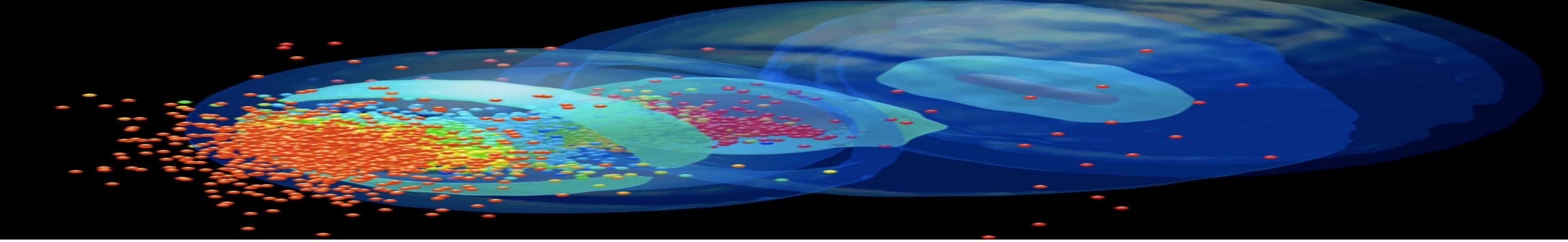


# Recent Progress on High Quality Electron beam Generation through Plasma Based Acceleration at L2PA of Tsinghua University


Wei Lu

Tsinghua University


The 5$^{th}$ IPAC

June 17$^{th}$ 2014 , Dresden Germany

# Major Collaborations

- **UCLA**

Chan Joshi and Warren Mori

- **NCU**

H.H. Chu and J. Wang

- **SLAC**

Mark Hogan and FACET team

- **ANL**

Wei Gai

- **BNL**

Igor Pogoresky and Ilan Ben-Zvi

# Outline

- **L2PA Overview:**
  - ◆ **The people**
  - ◆ **The mission**
  - ◆ **The facilities**

- **The Work (a few samples)**
  - ◆ **Theory and simulation**
  - ✓ **Ionization Injection Methods for Future Light Sources**

    **Xu et al., Phys. Rev. Lett. 112, 035003 2014**
    **Li et al., Phys. Rev. Lett. 111, 015003 2013**
    **Xu et al., Phys. Rev. STAB 17,061301 2014**

  - ◆ **Experiments (LWFA)**
  - ✓ **Generation of 20-30MeV electron beams with very low absolute energy spread**
  - ✓ **~80MeV mono-energetic electron beams via single stage ionization injection**
  - ✓ **~300-430MeV low energy spread (2-5%) electron beams using a 36fs 50TW laser**

- **Future Perspective**

# $L^2PA$

## Laboratory of Laser Plasma Physics and Advanced Accelerator Technology at Tsinghua University

**Yingchao Du**

**Accelerator Physics**

**Jianfei Hua**

**Laser-plasma acceleration**

**Wei Lu**

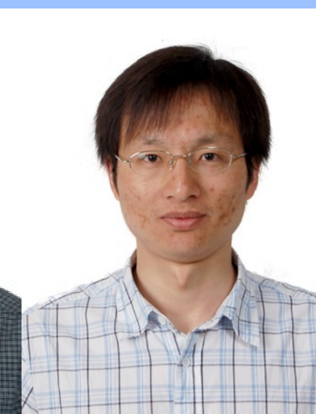
**Laser Plasma Physics and Plasma Acceleration**

**Chih-Hao Pai**

**Laser-plasma interactions**

**Jiaru Shi**

**Accelerator Physics**



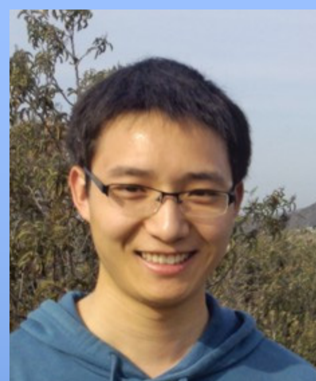
**Lixin Yan**

**Accelerator Physics and THz Technology**

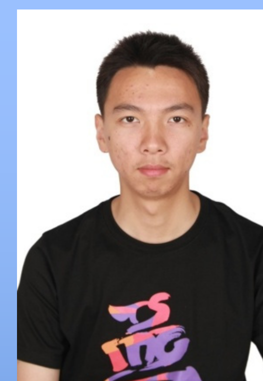
# $L^2PA$

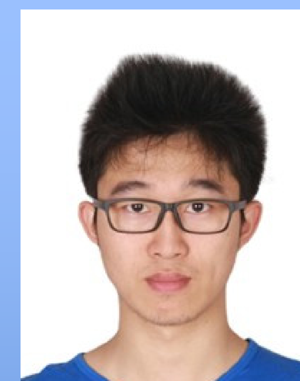
## Laboratory of Laser Plasma Physics and Advanced Accelerator Technology at Tsinghua University

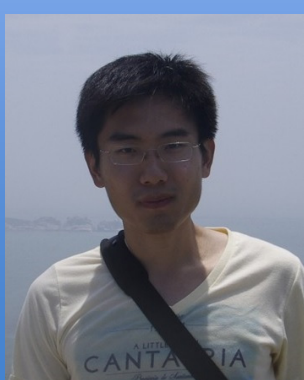

Xinlu Xu


Chaojie Zhang


Fei Li


Yang Wan


Yipeng Wu


Bo Guo


Xiaohui Zhang


Zhi Cheng


Shan Huang


Jie Zhang

# Current Research Focus

## Key physics of high quality plasma based accelerators

- **Stable and efficient acceleration structure**

➢Matched self-guiding、fully optical channel generation、channel assisted matched guiding…

- **High quality controlled injection and 6D phase space manipulation**

➢ultralow emittance、high brightness、high charge and current、low energy spread、
short pulse duration、controllable profile…

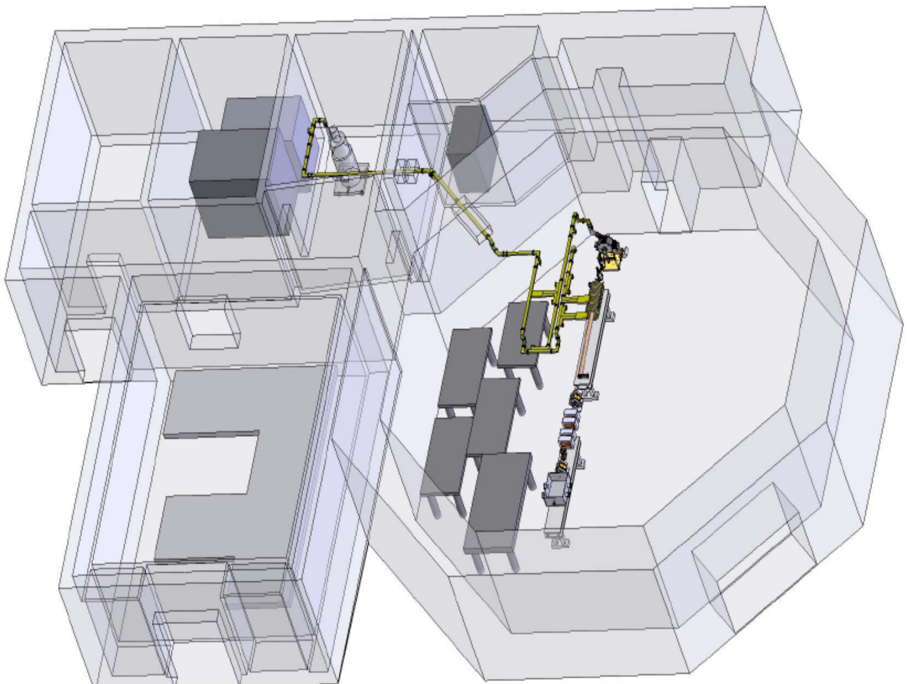
- **Diagnostics of beams with special space and time structures**

➢ultralow emittance、low energy spread、phase space structures…

- **Diagnostics for acceleration structure and dynamic processes**

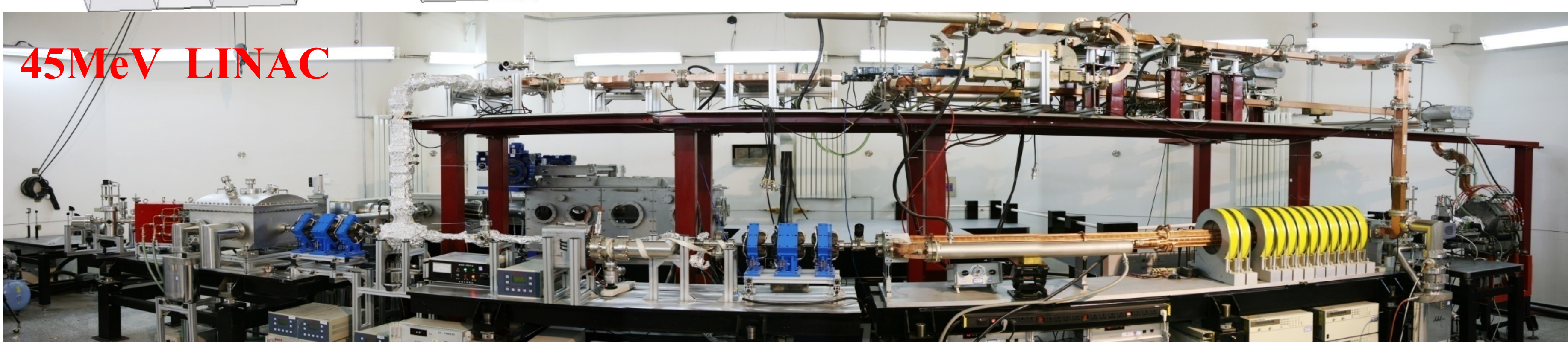
➢Optical probe、electron probe …

# Advanced Acceleration Platform Based on TTX



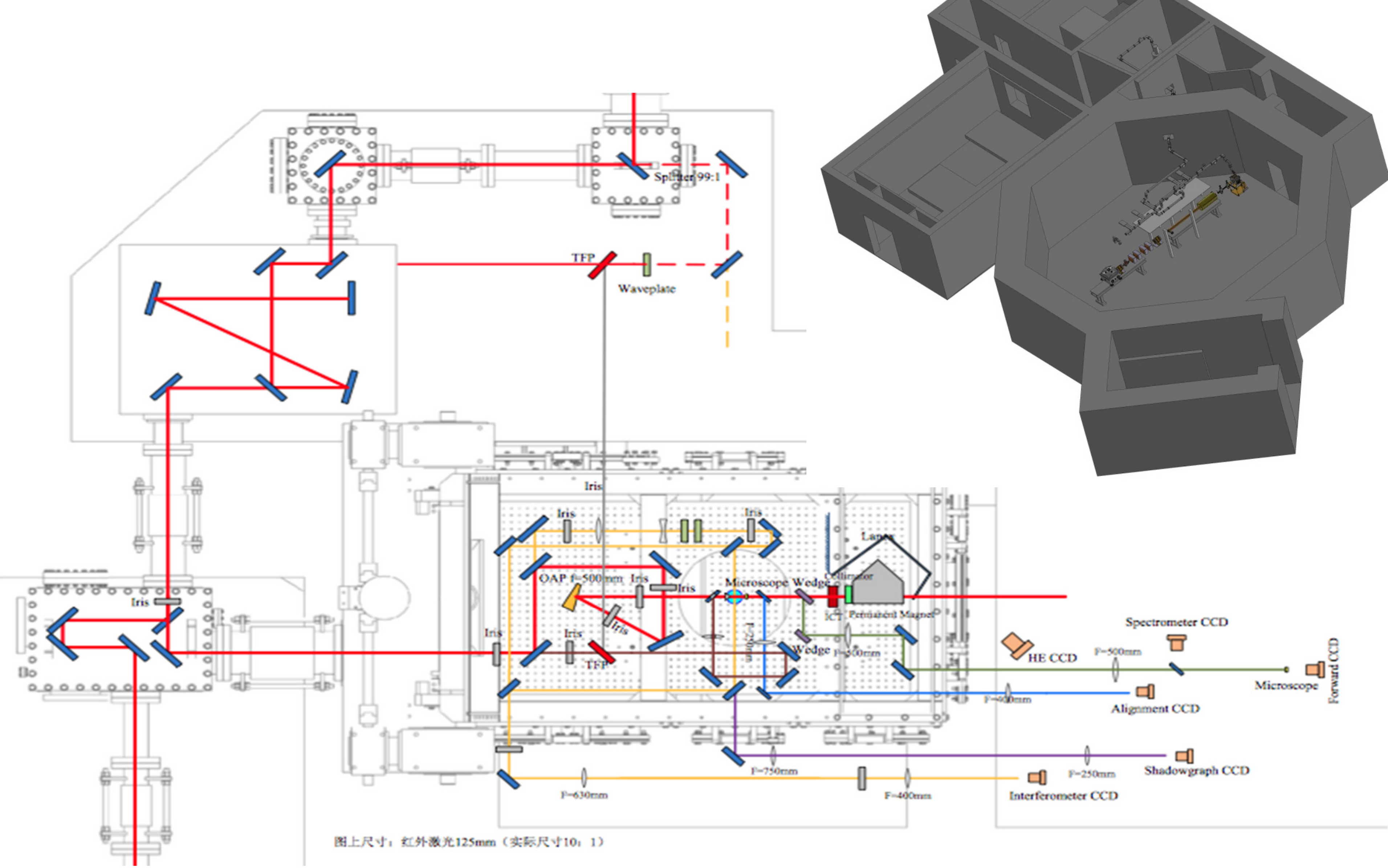
## 20TW Laser ＋45MeV Linac


20TW Laser System

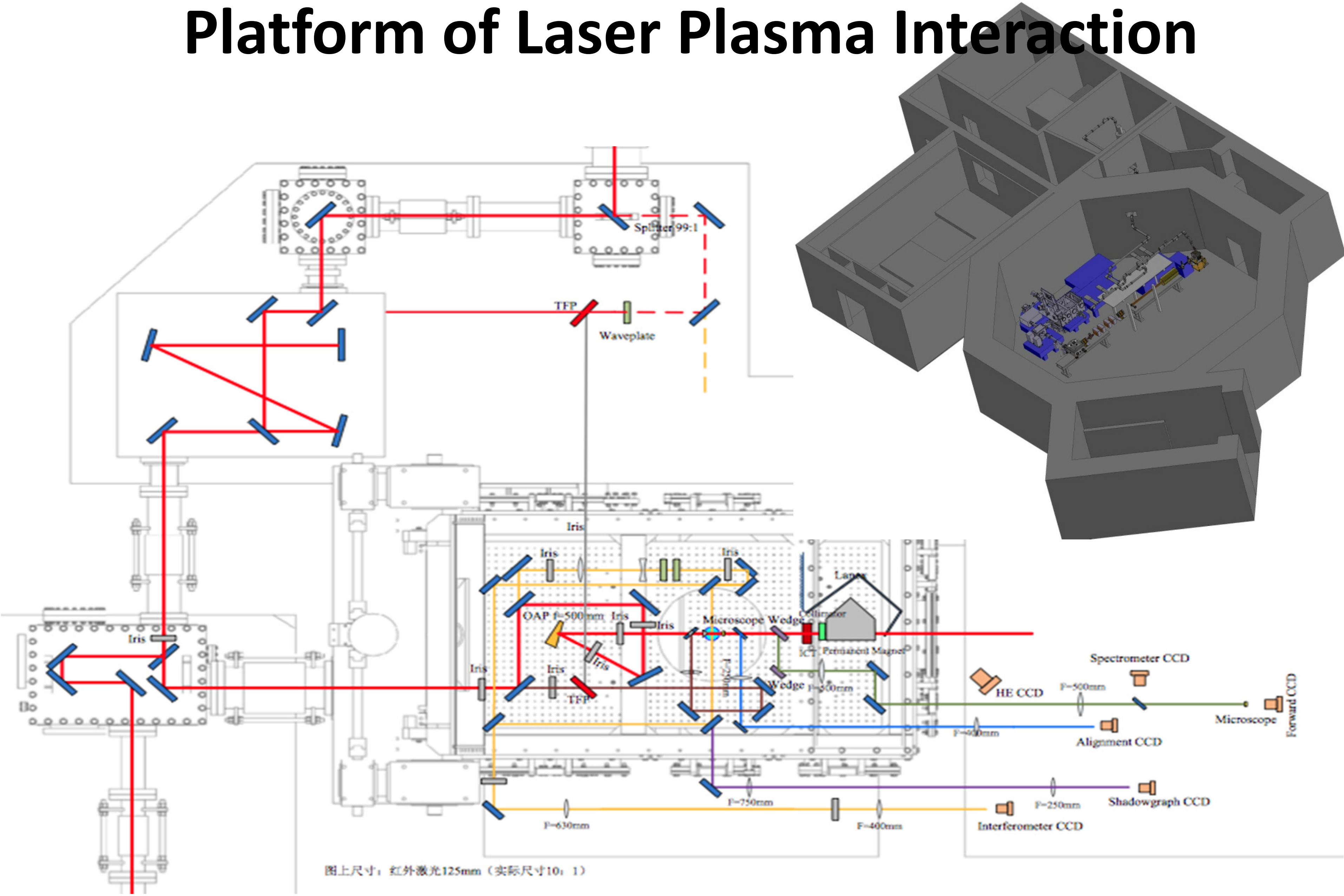



Electron bunch compression and laser upgrade (40TW) are currently underway

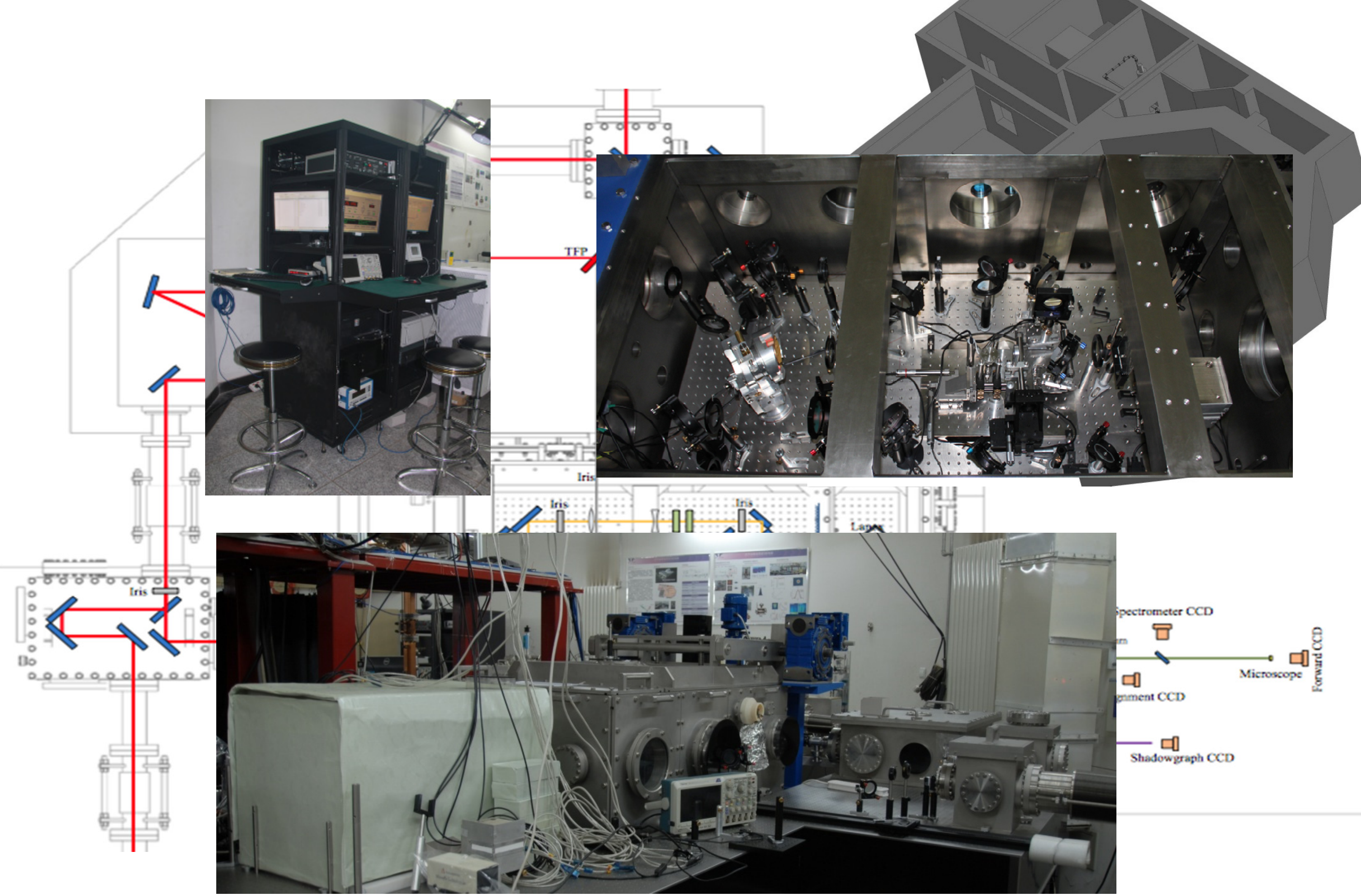
# Platform of Laser Plasma Interaction



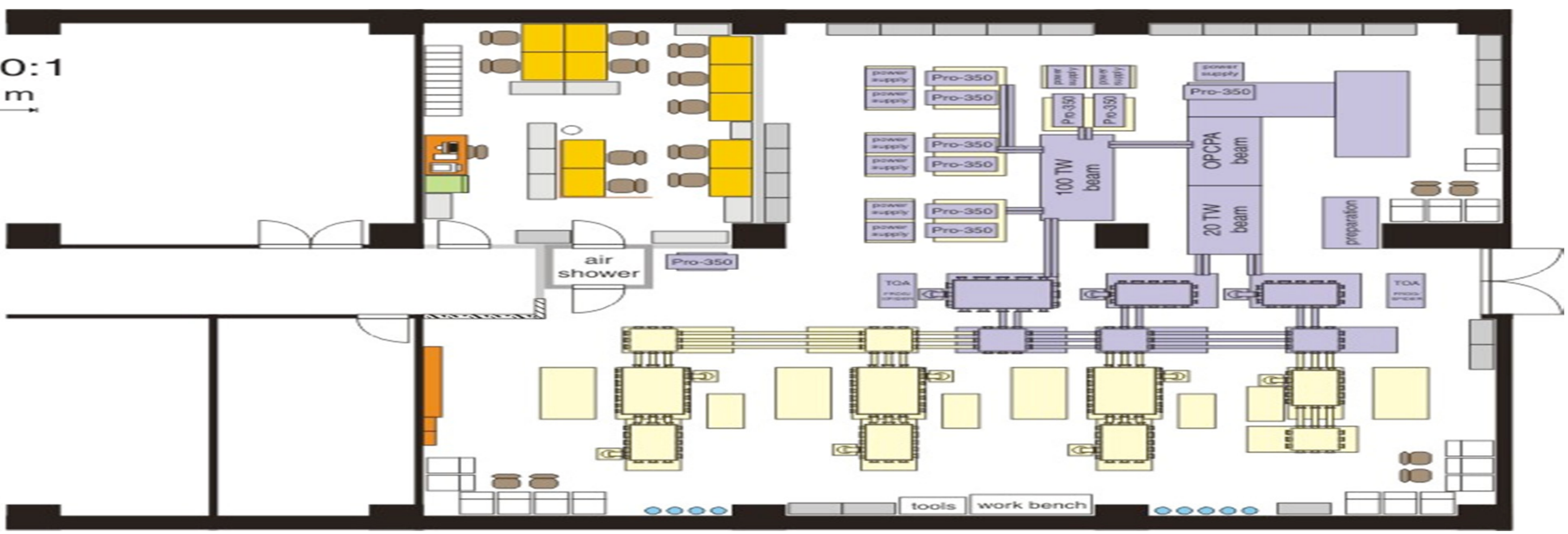
# Platform of Laser Plasma Interaction



# Platform of Laser Plasma Interaction

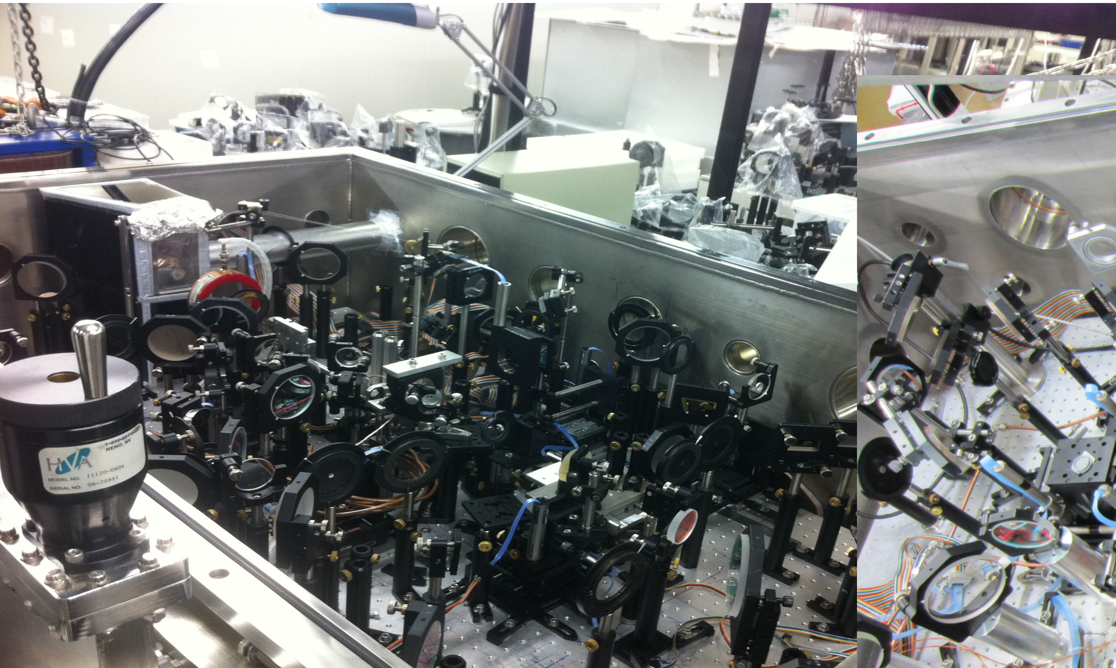


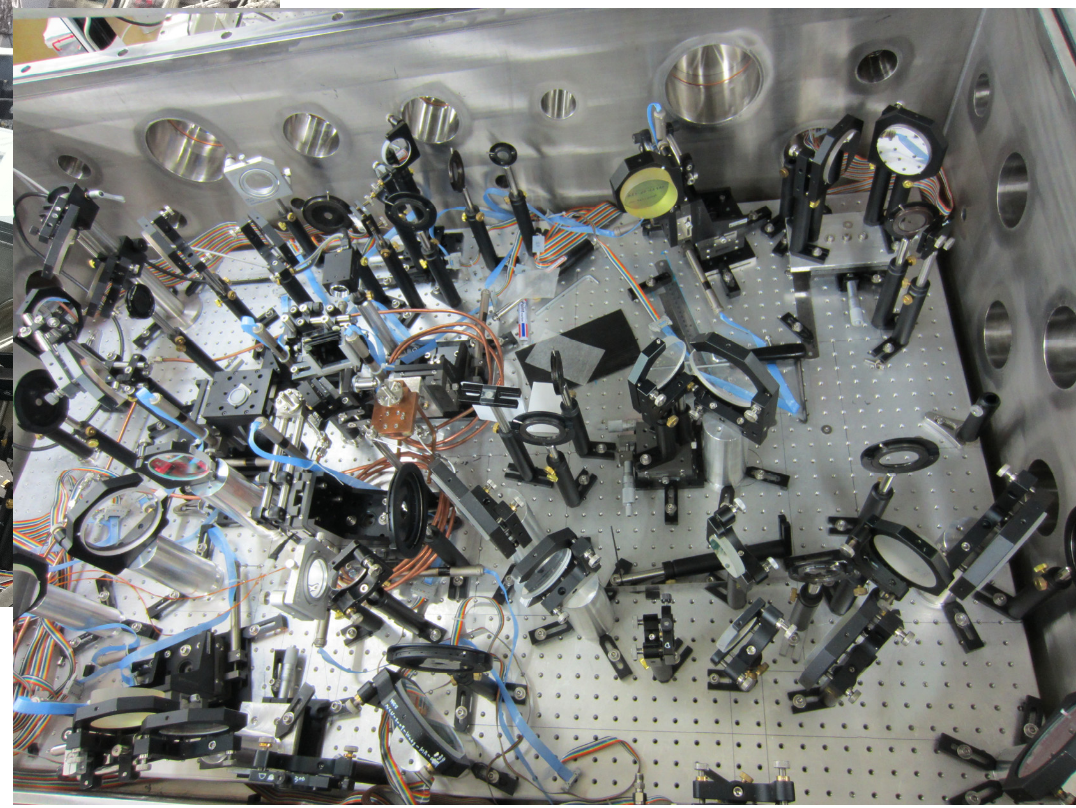
# NCU 100TW Multi-Pulses Facility
# (led by Prof. J. Wang at NCU)



# NCU/Tsinghua/UCLA Joint Platform for Laser Plasma Acceleration

**Chamber 2 for radiation source development**





Tsinghua team provides the manpower, ideas , simulation support and part of the running cost for experiments

**Chamber 3 for key physics study of LWFA**

# Theory and Simulation

- Phase space dynamics of ionization injection and  generation of ultra-bright electron beams through ionization injection in beam or laser driven wakes

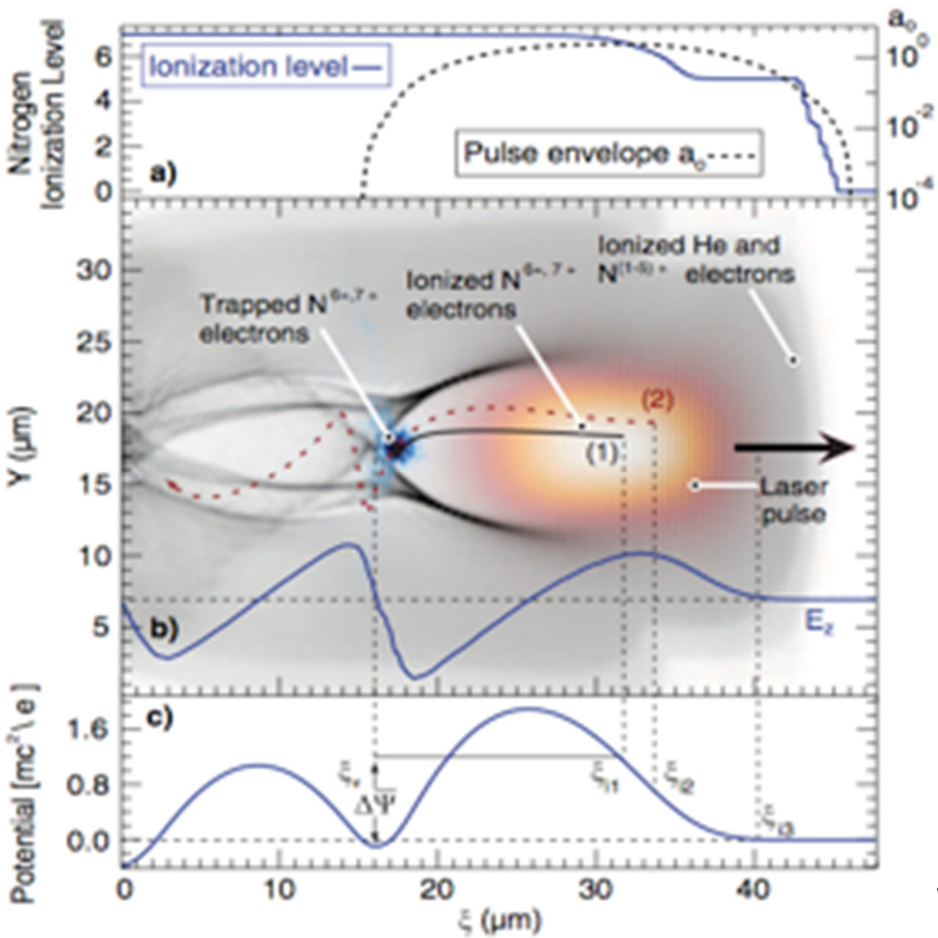
**Xu et al., Phys. Rev. Lett. 112, 035003 2014**

**Li et al.,  Phys. Rev. Lett. 111, 015003 2013**

**Xu et al., Phys. Rev. STAB 17,061301 2014 (Editors' Suggestion)**

# Ionization Injection

**Freeing electrons inside the wake: ionization**




$$\psi_{initial} > 0$$

making it easier for

$$\Delta\psi \equiv \psi_{final} - \psi_{init} < -1$$

**A laser can lead to a residual drift in the polarization direction.**

W. Lu Ph.D dissertation 2006 (3D theory)
E. Oz et al., PRL 2007 (exp + 1D theory)
A. Pak et al., PRL 2010 (exp+3D theory)

# Different Scenarios

- **Beam Driven Wake+ Beam or Wake field ionization**

➢ E. Oz et al., PRL 2007 (exp+1D theory)

- **Laser Driven Wake + Laser ionization**

➢ A. Pak et al., PRL 2010 (exp+3D theory)
➢ C. McGuffey et al., PRL 2010 (exp)
➢ C. Clayton et al., PRL 2010 (exp)
➢ B. Pollock et al., PRL 2011 (exp)
➢ J.S. Liu et al., PRL 2011 (exp)
➢ Intense transverse colliding pulses: M. Chen et al., AIP proceedings 2012 (sim)

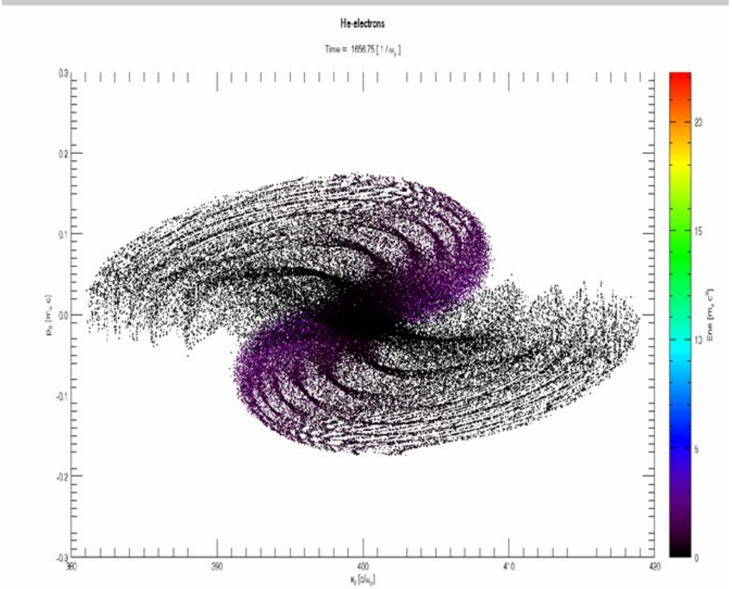
- **Beam Driven Wake + Laser ionization**

➢ Longitudinal injection: B. Hidding et al., PRL 2012 and LPAW 11; Lu et al., LPAW11 (sim)
➢ Transverse colliding pulses injection: F. Li et al., PRL 2013 (sim)

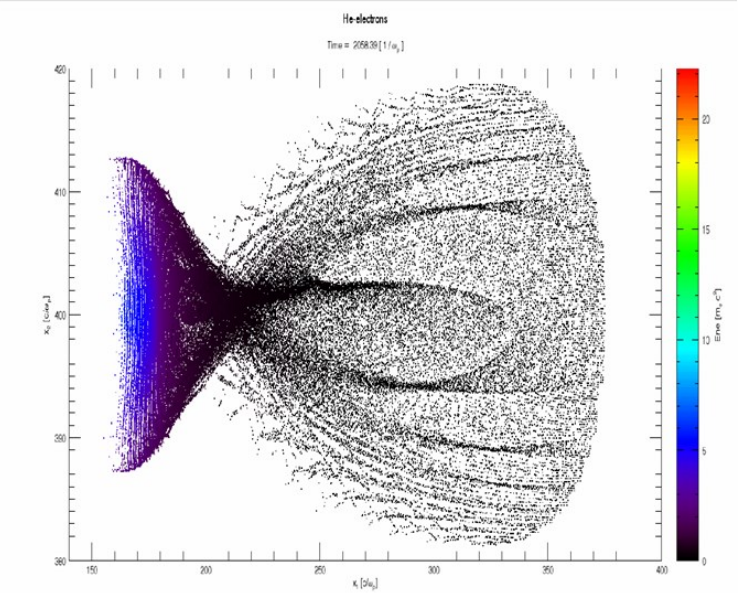
# The Key Physics:

# Transverse and Longitudinal Phase Mixing

### Transverse Phase Mixing

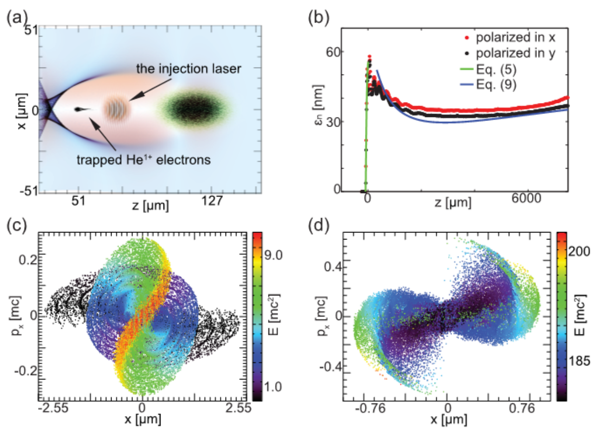


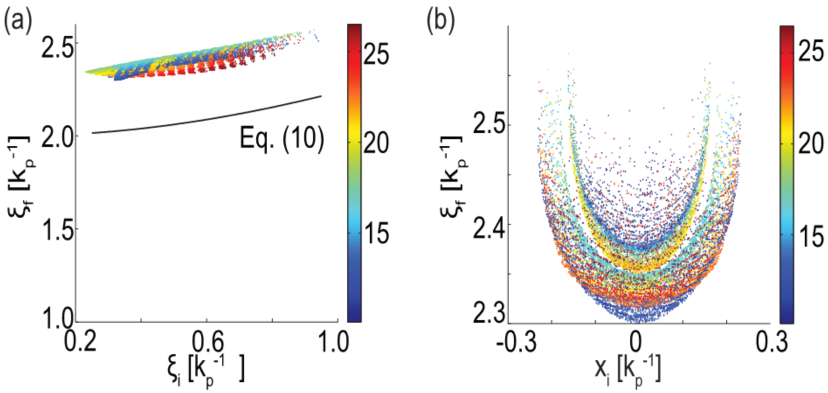

### Longitudinal Phase Mixing



# Theoretical Model for Phase Space Dynamics of mixing

**The model can explain quantitatively the induced emittance dynamics, such as the initial anomalous growth, oscillation, decay and saturation.**



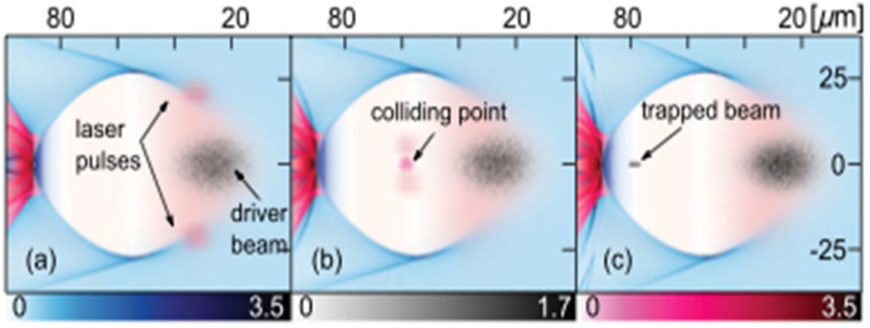

X.L. Xu et al., Phys. Rev. Lett. 112, 035003 2014

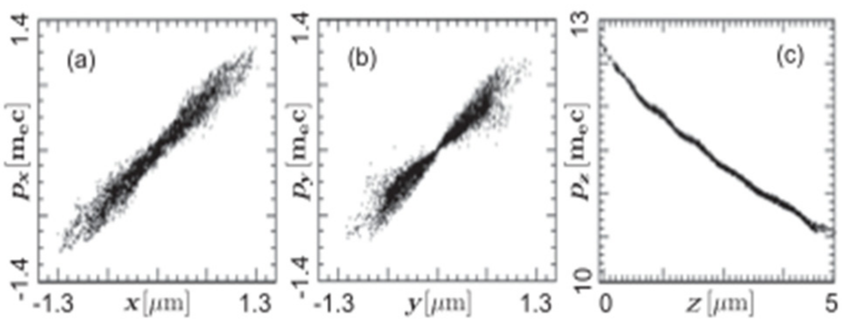
# Ionization Injection by Transverse Colliding Pulses in PWFA

F. Li et al., PRL 111,015003 (2013)

**Key factors:**

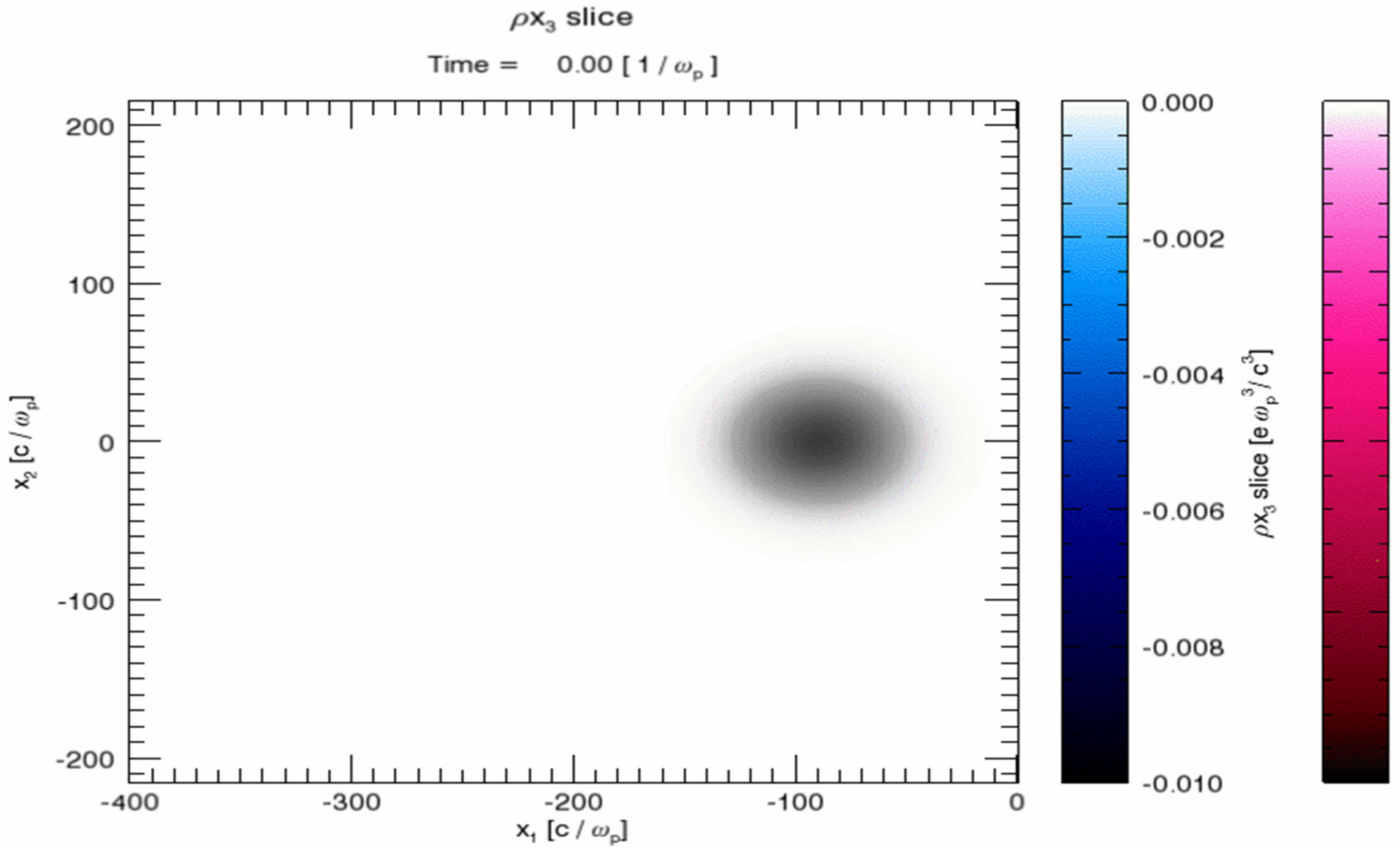
- **Laser polarization ( z, beam path)**
  - reducing thermal emittance
- **Laser intensity ( weak)**
  - nearly no perturbation of wake
  - No random heating by colliding pulses
- **Very short overlapping (injection) time**
  - Much less phase mixing




**As a result, it could lead to very good beams through optimization:**

- Low normalized emittances (**~1-10 nm**)
- High current, short pulse (**~.1-1kA, ~fs, few pC**)
- Low energy spread (**~1-10keV** for slice, **~.1%** level for total)

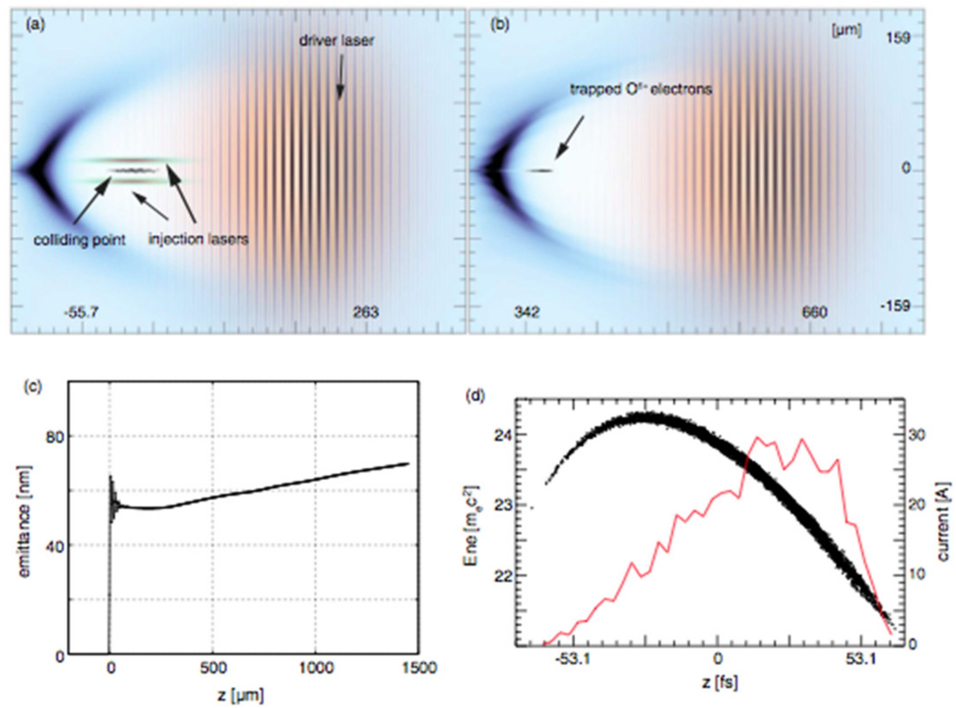

ρx3 slice
Time = 0.00 [ 1 / ωp ]
200
100
0
-100
-200
x2 [c / ωp]
-400
-300
-200
-100
0
x1 [c / ωp]
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
ρx3 slice [e ωp3 / c3]

## Ionization Injection by Transverse Colliding 400nm Laser Pulses in High Power CO2 Laser Driven Wakes

Xu et al., Phys. Rev. STAB 17,061301 2014 **(Editors' Suggestion)**

**Key factors:**

- **Long wavelength CO2 Laser driven wakes**
  - ➢ large ponderomotive force at low intensity
- **Short wavelength injection Laser**
  - ➢ low ponderomotive force at high intensity
  - ➢ weak perturbation to the wake
  - ➢ weak random heating by colliding pulses
- **Very short overlapping (injection) time**
  - ➢ much less phase mixing
  - ➢ low slice energy spread (~30keV)



# Experiments

- Generation of 20-30MeV electron beams with very low absolute energy spread using a 60fs 5TW laser

- ~80MeV mono-energetic electron beams via single stage ionization injection using a 40fs 8TW laser

- ~300-430MeV low energy spread (2-5%) electron beams using a 36fs 50TW laser

# Very low energy spread (absolute and relative) electron beams via LWFA

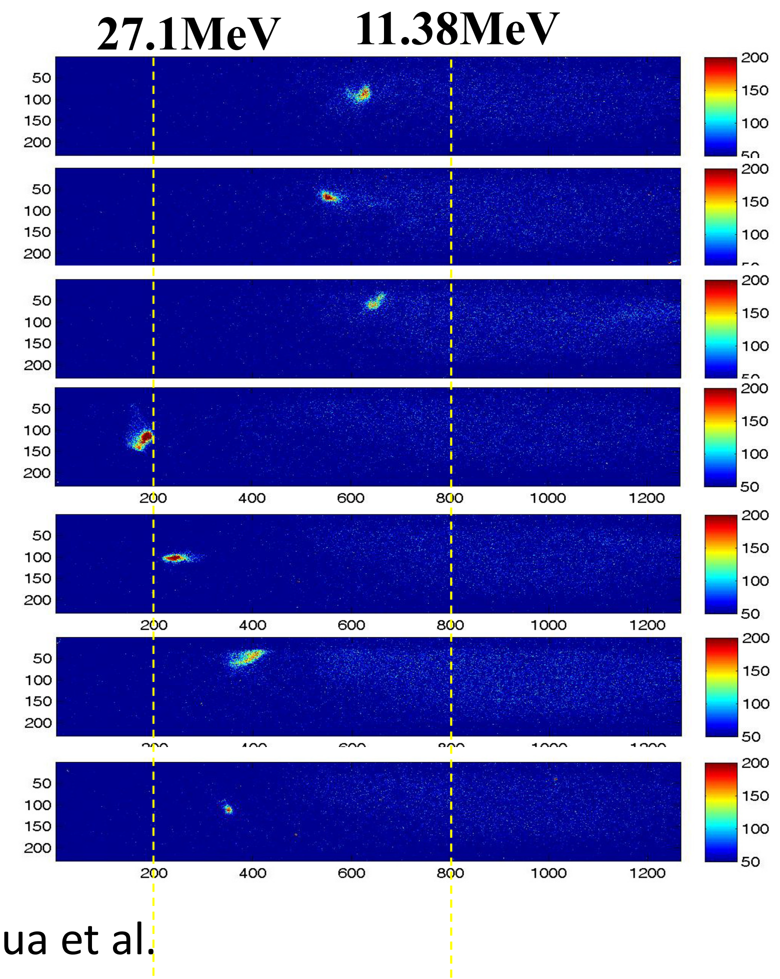
**10-40MeV pC mono-energetic electron beam generation by a 60fs 5TW laser**

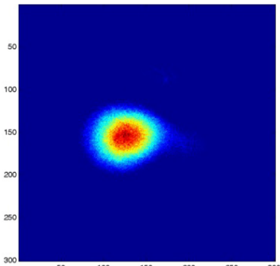
**Very low absolute energy spread (AES) and relative energy spread (RES) observed under proper conditions :**

On many shots, **AES** below **0.5MeV** (rms), with the lowest **0.18MeV**

On many shots, **RES** around 1-2% (rms), with the lowest **0.8%**

**Small divergence of a few mrad, with the smallest 1.2mrad**



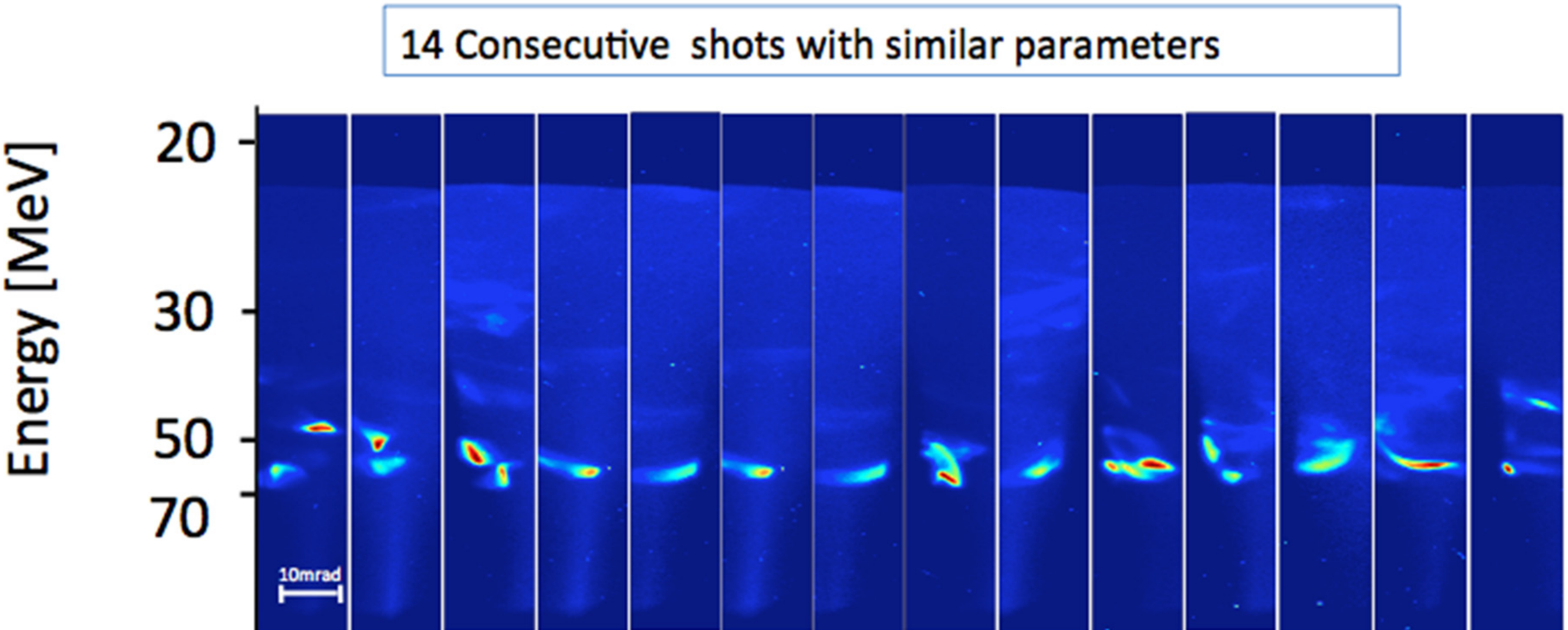



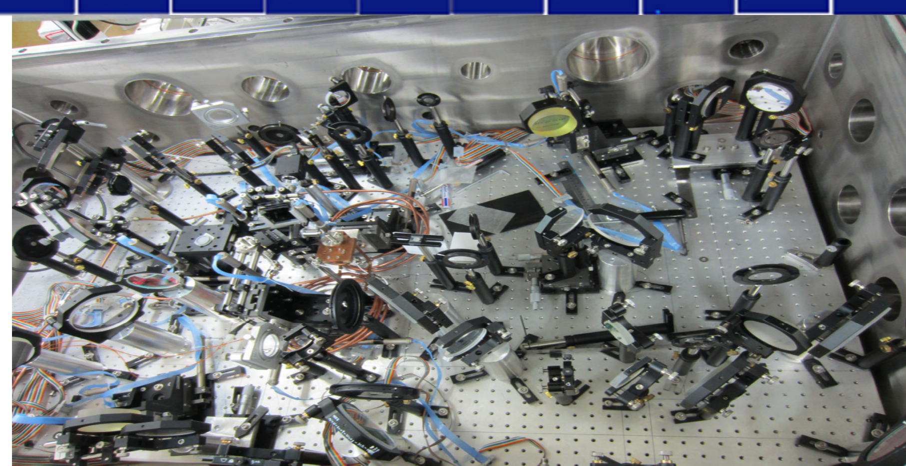
**Laser Parameters:**

**Pulse Energy: ~300-400mJ**
**Pulse Duration: ~60-70fs**
**Laser Focal spot W0: 12um**

By J.F. Hua et al.

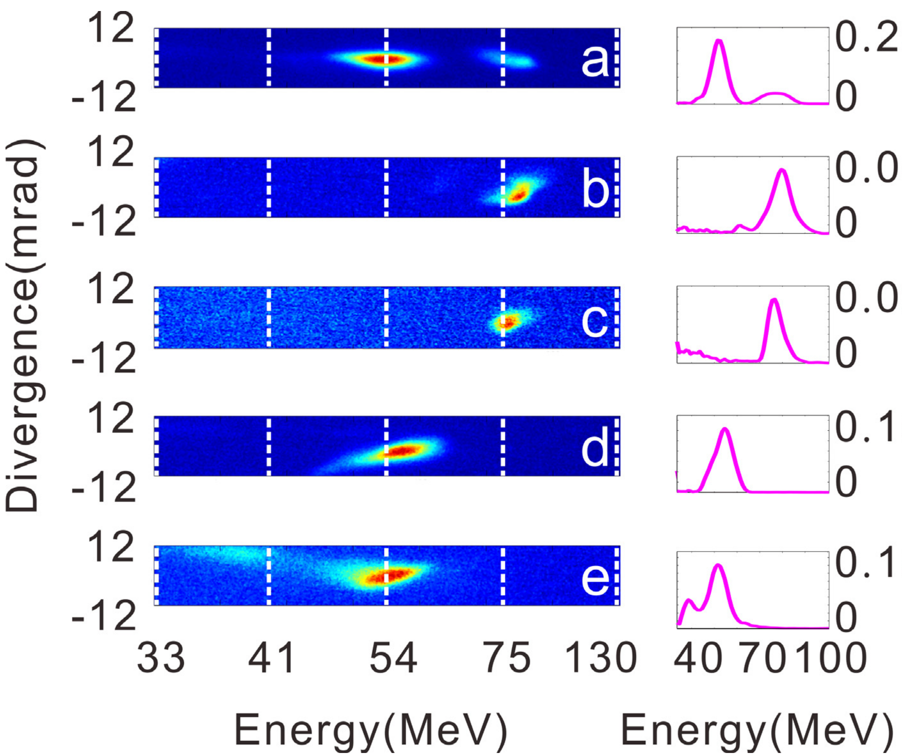
# Similar Features observed with better repeatability using a 35fs 10TW laser



By C.H. Pai et al.,

# Mono-energetic Electron Beams through single stage Ionization Injection




**Laser Parameters:**

**Pulse Energy: ~400mJ**

**Pulse Duration: ~45fs**

**Laser Focal spot W0: 12um**

**Gas mix: N2 (5%) and He**

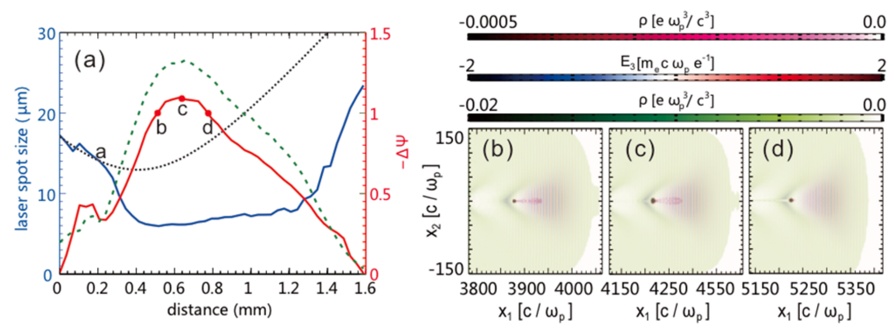
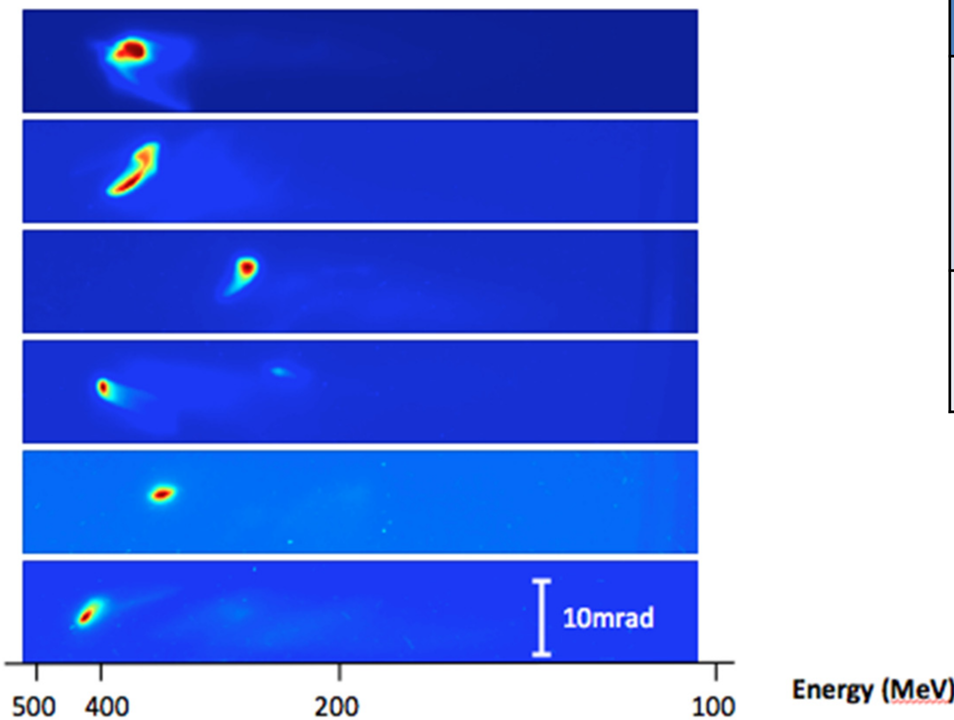



**Figure 4.** Laser evolution and injection process. Laser spot size is shown by the blue solid line, and black dashed line represents the laser spot in vacuum. Self-focusing occurs when the plasma density is higher than the threshold, indicated by point a in figure (a). Red solid line shows $-\Delta\Psi$, which should be larger than 1 to trigger the injection process. Green dashed line shows the maximal electric field on axis, which has a similar evolution with $-\Delta\Psi$. Injection begins at point b in figure (a), and ends at point d. The corresponding density map is shown in (b) and (d).

**The key physics:**
**Laser evolution shortening The injection length to 200um (3D PIC)**

By C.J. Zhang et al.,

# 300-430MeV low energy spread (2-5%) electron beams using a 36fs 50TW laser




| Experimental Parameters | | |
|---|---|---|
| laser | Energy | ~2J on target |
| | Pulse duration | 36fs |
| | Spot size | 30um (H) 25um (V) |
| Plasma (pure He) | density | 5.6E18 /cm3 |
| | Length | 4mm |

| Energy (MeV) | RMS Energy spread |
|---|---|
| 377 | 5.5% |
| 367 | 5.2% |
| 265 | 2.1% |
| 408 | 2.3% |
| 334 | 2.3% |
| 435 | 3.6% |

Note:
the energy spread caused by beam angular spread has not been removed, therefore the real energy spread could be smaller!

# Future Perspective

- Plasma based accelerators seem to have a bright future!
- Plenty of Ideas for boosting the beam brightness and reducing the energy spread
- Big challenges remain for colliders, but many ideas exist for further study!
- Be positive is important in the uncharted water, where new discoveries could be rich
- A dream facility? a high charge Linac combined with multi-color high power lasers

**Thank you for your attention!**