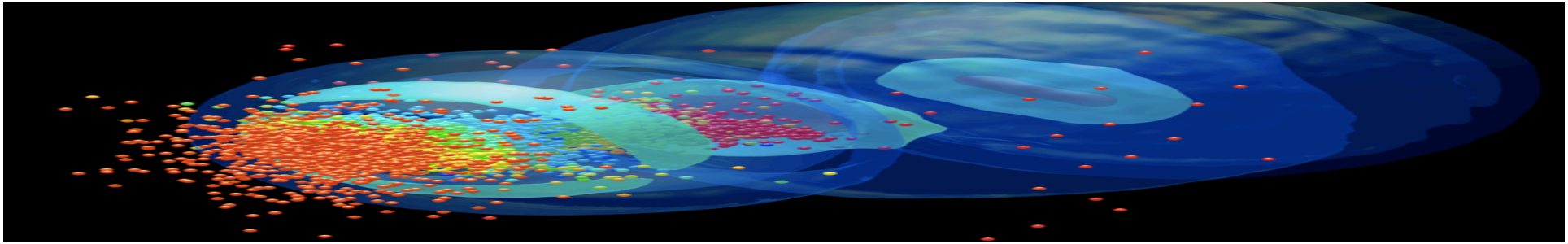

Key Physics Study of Laser Wakefield Acceleration Utilizing Ultrafast CO2 Laser and Electron Beam at ATF

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The 17th ATF User Meeting

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Outline

- **Some Key physics of LWFA study**
- **Similarity of collisionless Laser Plasma interaction: wavelength scaling**
- **Ultrafast CO2 driven LWFA: some advantages**
- **Proposed LWFA experiments with near term ATF capabilities**
  - **Self-injected multiple-bubble regime for CO2 LWFA**
  - **Transverse and longitudinal electron probes for CO2 LWFA snapshot**
  - **Two-color ionization injection scheme for CO2 LWFA**

Some key physics of high quality LWFA

- **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 …

Similarity of collisionless Laser Plasma interaction: wavelength scaling

- For fully ionized collisionless plasma, all physical processes of laser plasma interaction are the same if the physical quantities are normalized to certain standard units that scale with laser wavelength

- For similar physical process , the real physical quantities scale with laser wavelength to certain power: velocity, momentum , power and current to 0th power, charge, length, emittance and pulse duration to 1st power, etc …

- This similarity can be broken if some absolute quantities are involved, such as ionization process

Ultrafast CO2 driven LWFA:

Some advantages comparing with 0.8um laser

- For given laser power and number of laser periods, the self-injected electron beam in CO2 LWFA has the same energy and current structure, but with 12.5 times longer duration and 12.5 times more charge and 12.5 times larger emittance: **Much easier to measure, therefore can be very useful for studying the physics!**

- For CO2 LWFA, similar physical process occurs at much lower plasma density with 12.5 times larger structure sizes, making it much easier to demonstrate **high quality external injection and acceleration**

- The large wake structure size also makes it much easier to take **wakefield snapshots using longitudinal and transverse electron probes**, due to its much less demands on spatial and temporal resolutions.

- For given laser intensity, the ponderomotive potential of CO2 laser is 150 times larger than that of the 800nm laser, and this makes it possible to utilize ionization based injection methods to obtain electron beams with low emittance (10s of nm) and high brightness.

- This can be achieved through separating the wake excitation and ionization injection process: using CO2 laser to driven a strong wake and using a 10mJ 30fs 800nm laser to free the injected electrons

A CO2 LWFA Program at ATF/ATFII

- With the currently available ps TW CO2 laser and the 80MeV ultrashort electron beam at ATF, a research theme focusing on the fundamental physics of LWFA described above can be readily started.

- With upgrade of ATF CO2 laser to 100TW in future, these ideas can be naturally extended to much broader parameter space

Proposed Experiments with current and near term ATF conditions

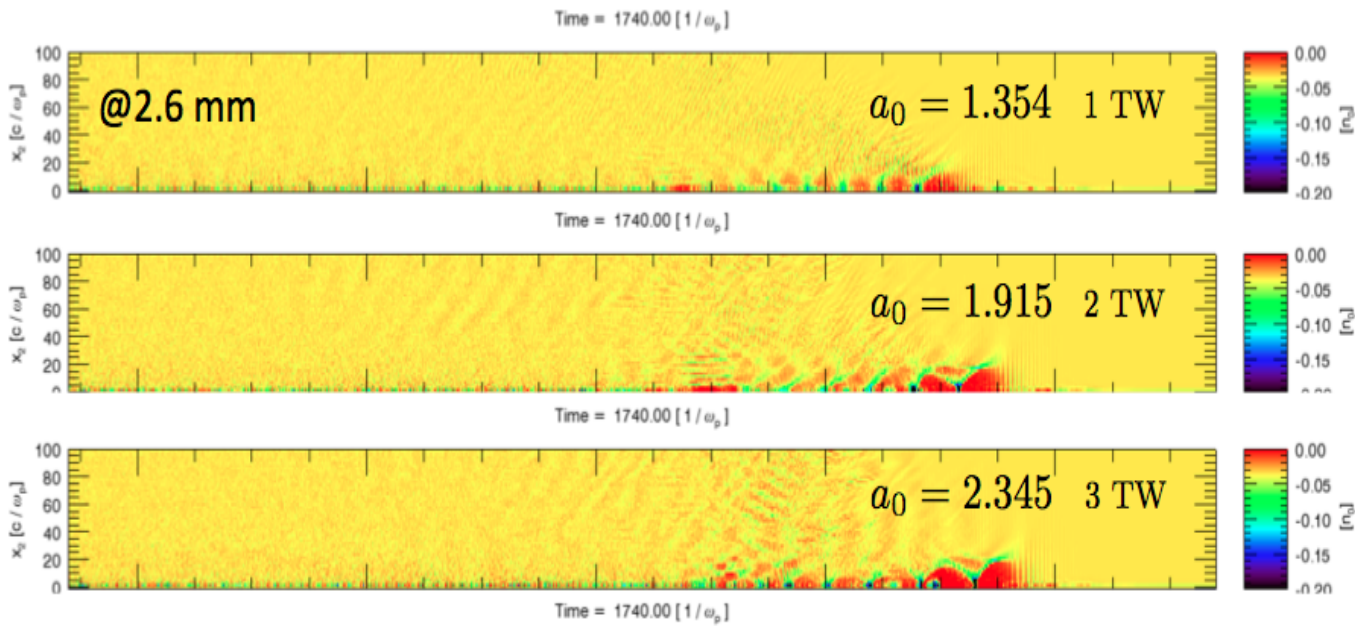
- Exp1: LWFA in the self-guided self-injected blowout/ bubble regime using 1-2ps 1-5TW CO2 laser: easy to setup, interesting physics, within 1 year

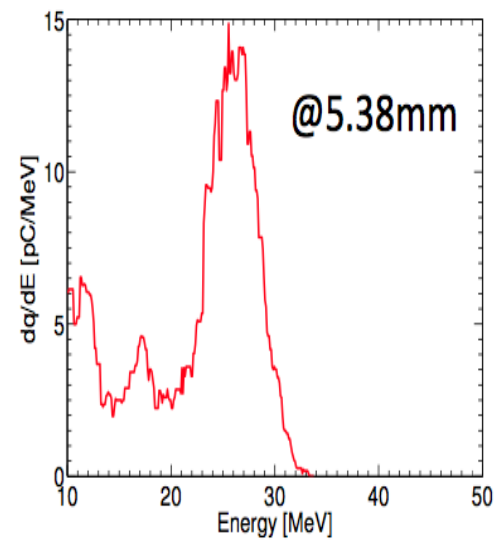
- Exp2: 80MeV transverse or longitudinal electron probes for 2ps 1TW CO2 LWFA snapshot: Physics is very good, setup with effort on modifying the laser route to PWFA chamber, within 1 or 2 years

- Exp3:Two-color ionization injection combining ps 5TW CO2 laser with a 10mJ 800nm laser: significant effort on laser and timing system development , within 2 or 3 years

Exp1: what could be expected?

- For 1-2ps 1-3TW CO2 with a focal spot 50um, and plasma density about 4*10^17cm-3, PIC simulations show that injections always occur, and sometimes with quasi-monoenergetic spectrum.

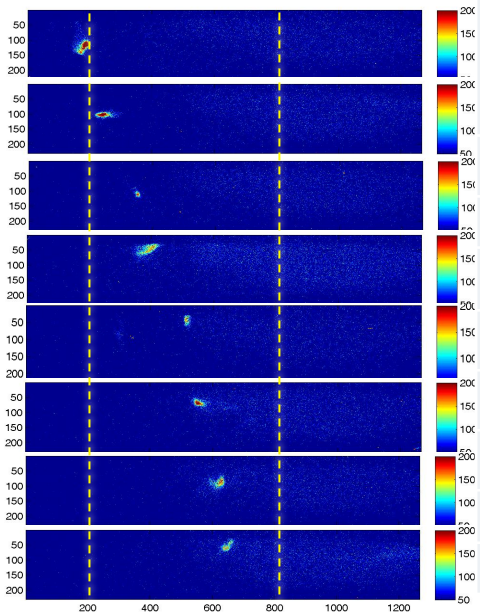




Real world can be more exciting!

2-5 TW 70-80fs 0.8um laser generating very high quality beam:

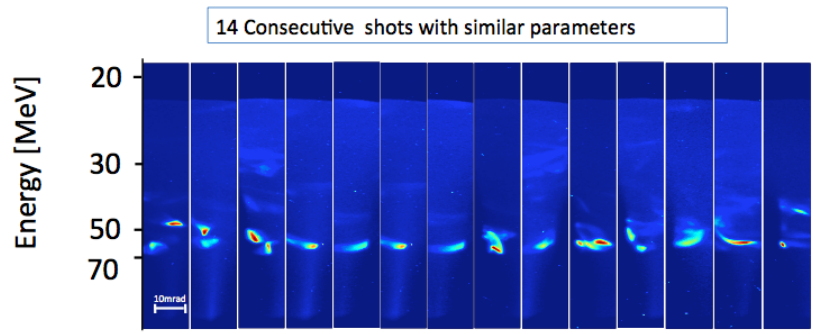
27.1MeV 11.38MeV



Energy (MeV)	Absolute energy spread(rms) (MEV)
27.6	0.53
25.7	0.77
22.1	0.18
21.0	0.87
17.5	0.20
16.5	0.53
14.7	0.45
14.3	0.39

1% level energy spread, potentially very short pulse and very low emittance, **but very hard to measure!**

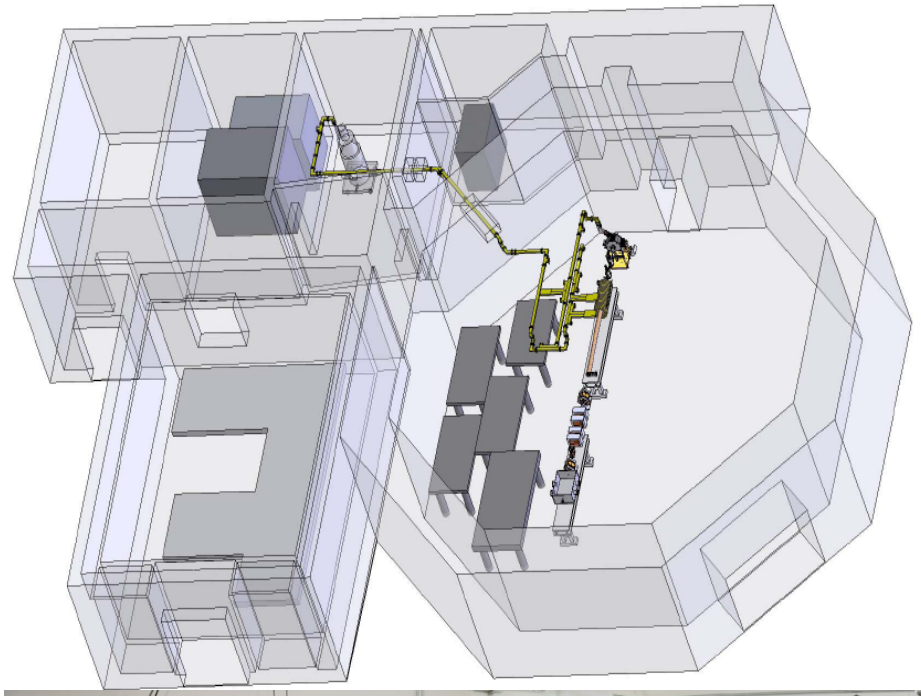
With a 3-8 TW 45fs 0.8um laser, good repeatability was obtained, even very highly nonlinear physics involved.



Scale to CO2, these parameters are close to The near term ATF parameters

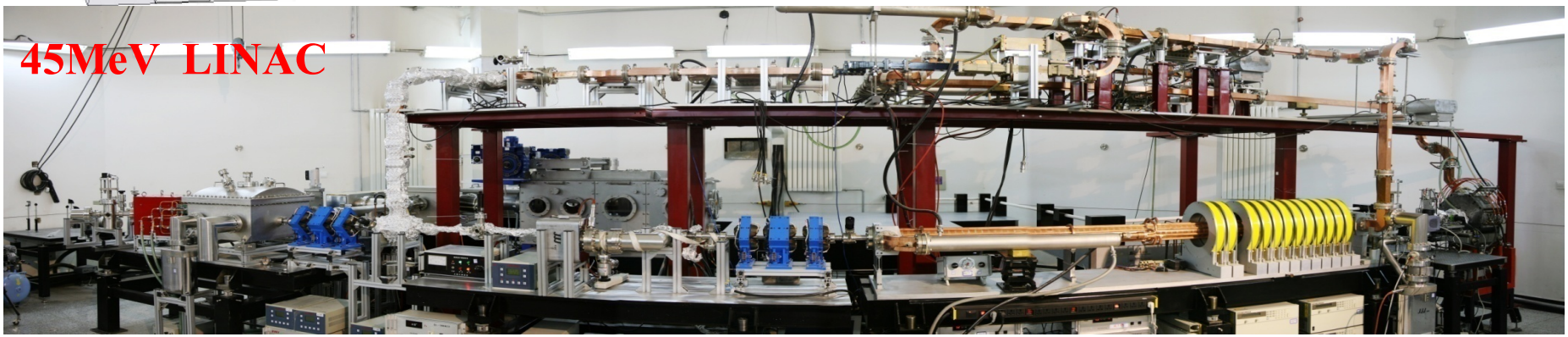
Experiment can be easily setup in the ion acceleration chamber or PWFA chamber

Advanced Acceleration Platform Based on TTX



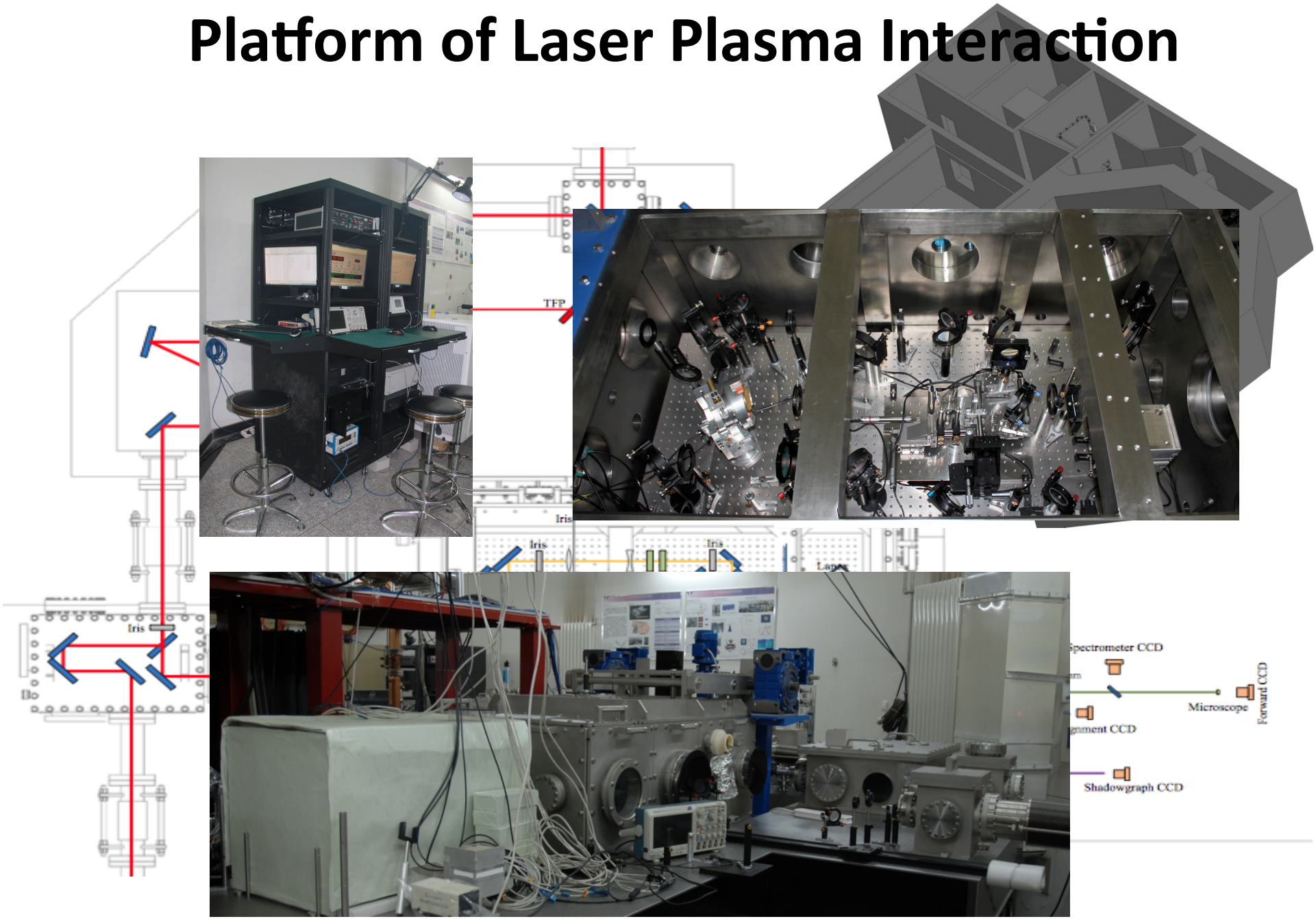
20TW Laser ＋45MeV Linac

20TW Laser System



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

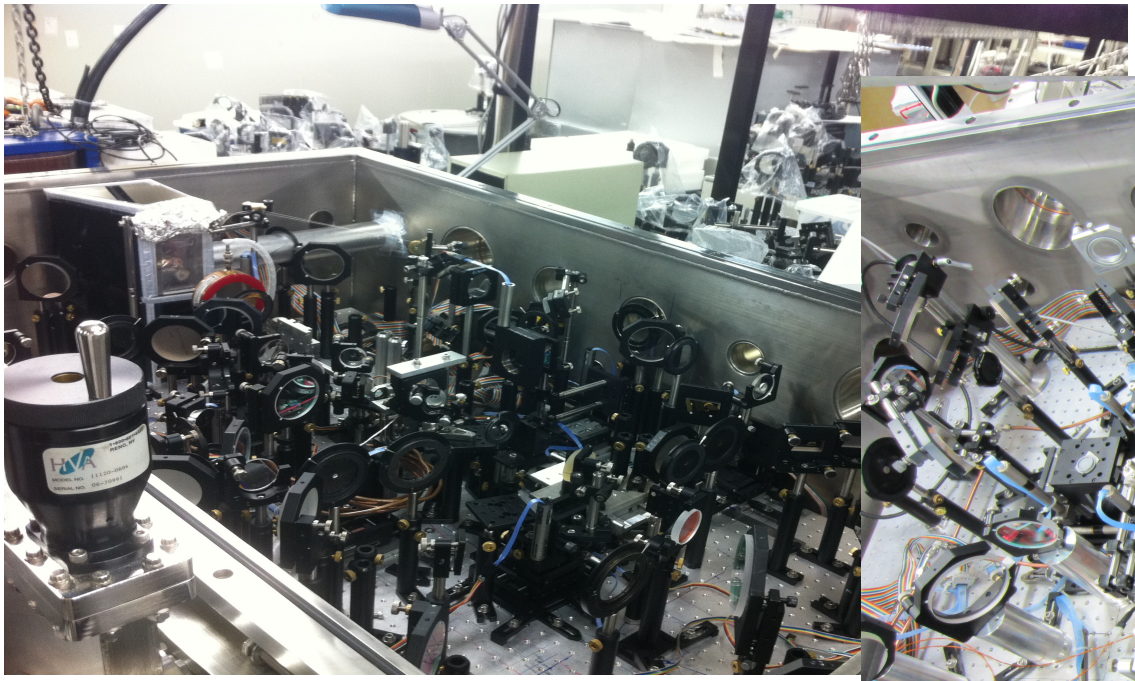
Platform of Laser Plasma Interaction

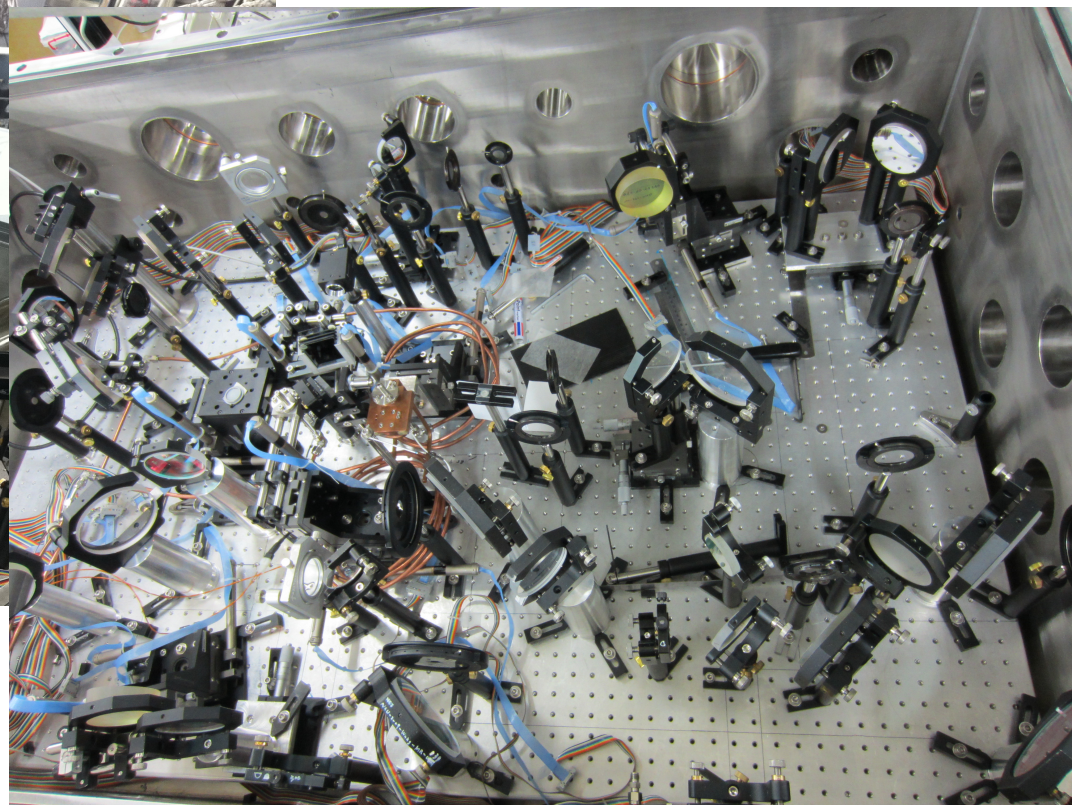


NCU 100TW Multi-Pulses Facility
(led by Prof. J. Wang at NCU)

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

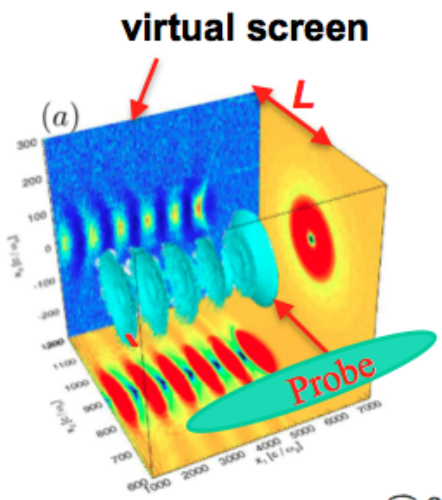
The goal of Exp1

- To demonstrate the self-injection of CO2 LWFA in the blowout/bubble regime, with a hope to get good beam!

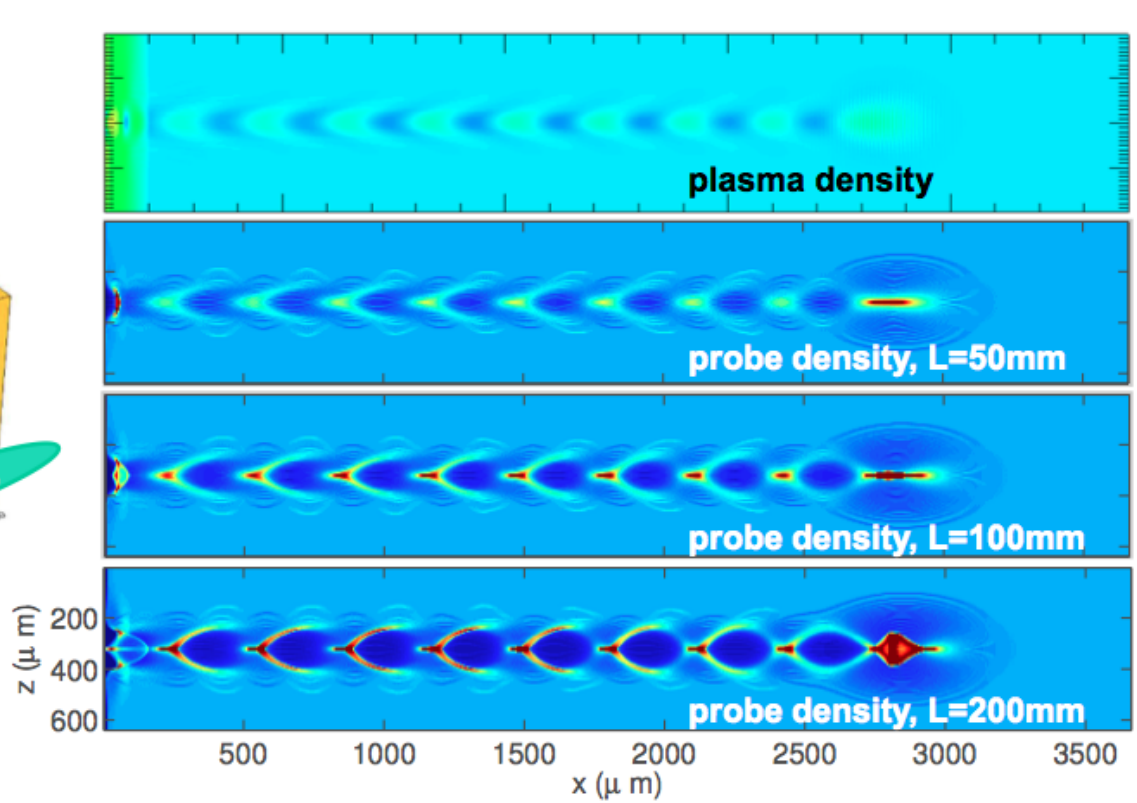
- To measure the beam properties carefully if mono-energetic beams can be generated

Exp2: CO2 laser wakefield imaging using 80MeV transverse electron probe

Basic concept:

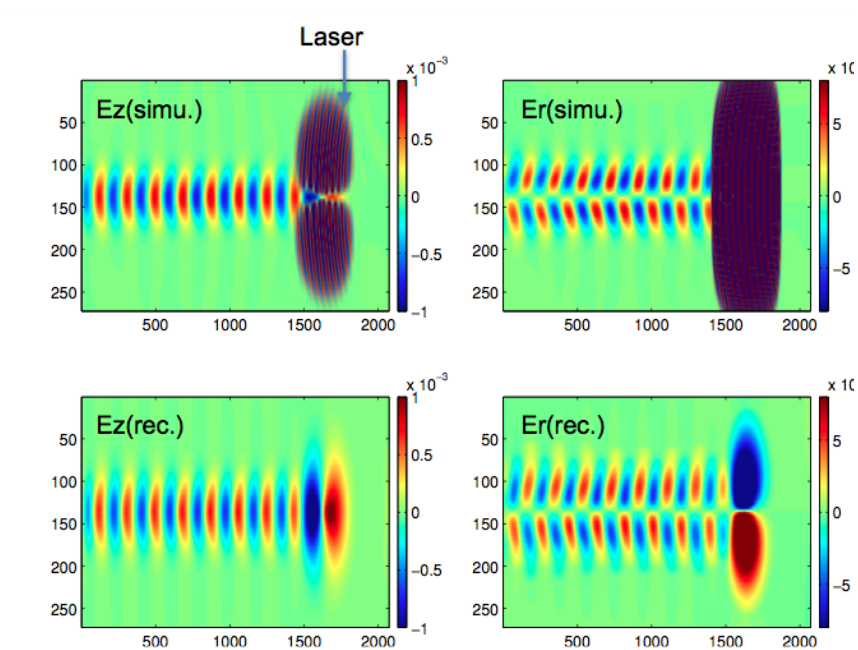


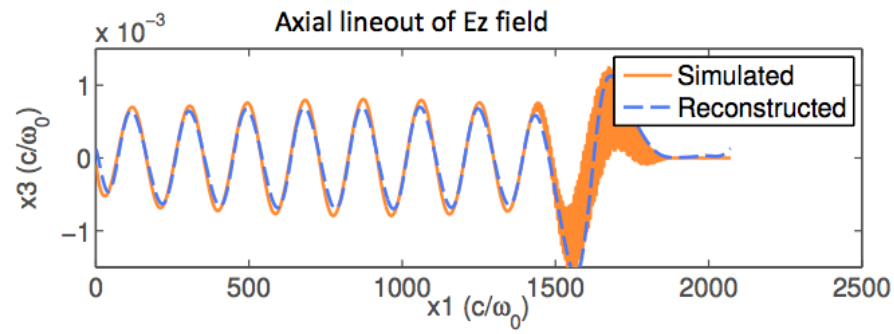
3D PIC simulation for a 200fs 80MeV electron probe:

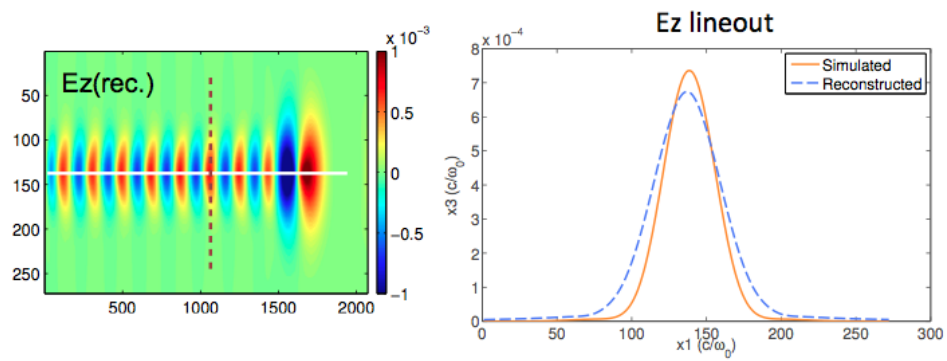


Plasma density 10^16cm-3, CO2 laser: 1ps 1TW 100um spot size

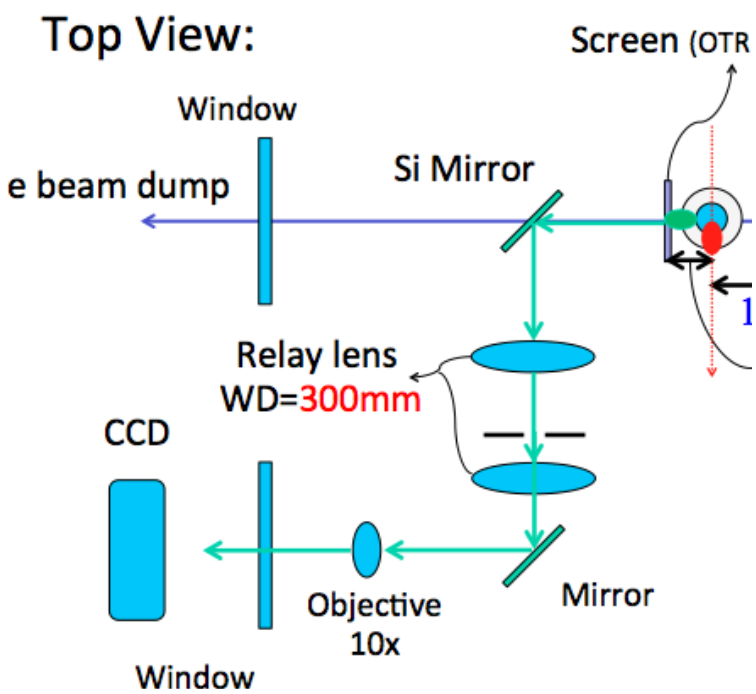
Comparison of simulation with reconstruction at 50mm

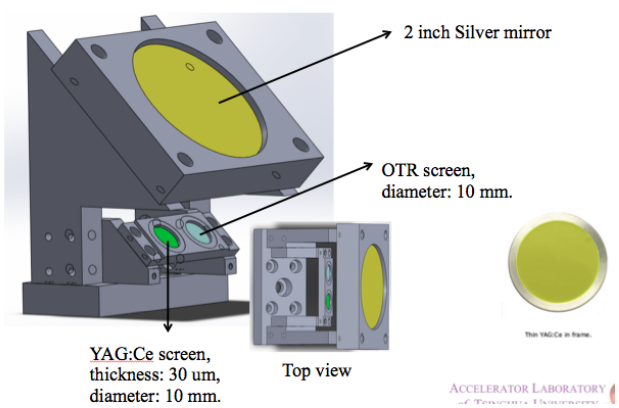






Basic setup and requirements





Electron focal spots: 3mm by 0.5mm

Timing jitter tolerance between laser and electron beam: ~5ps (OK!)

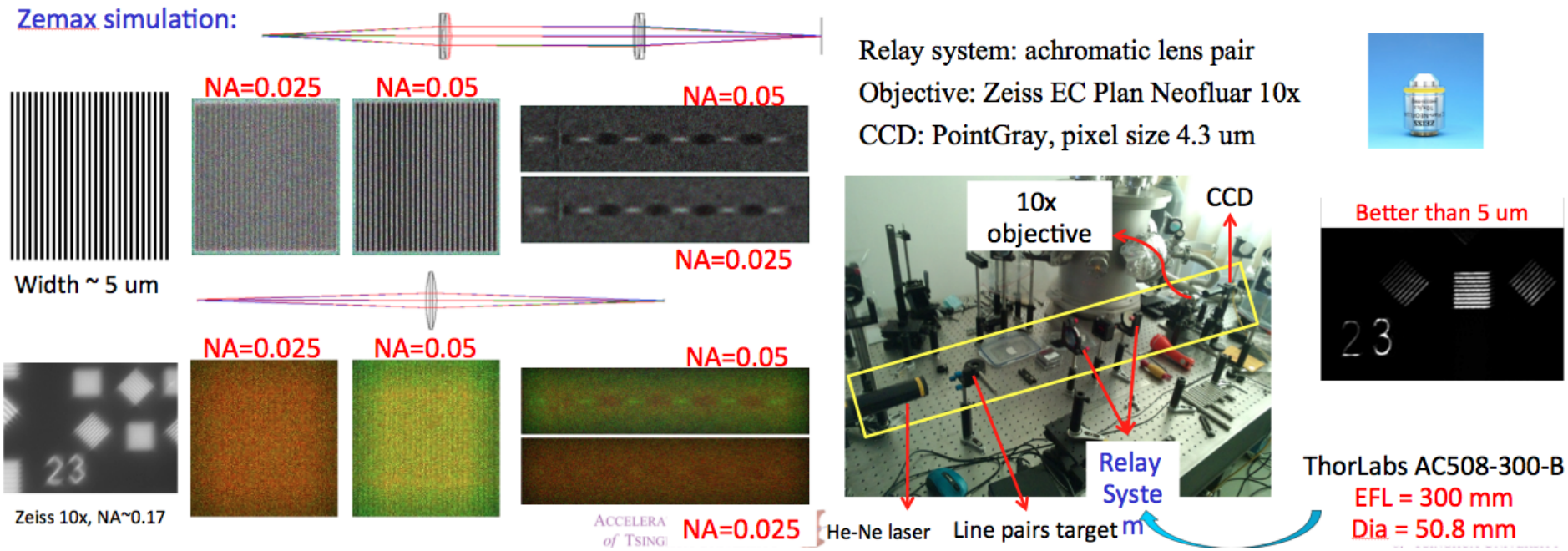
Electron pulse duration: < 300fs

Electron beam charge: >200pC

Screen: YAG:Ce or OTR

Spatial resolution: 5um

Imaging system and resolution test

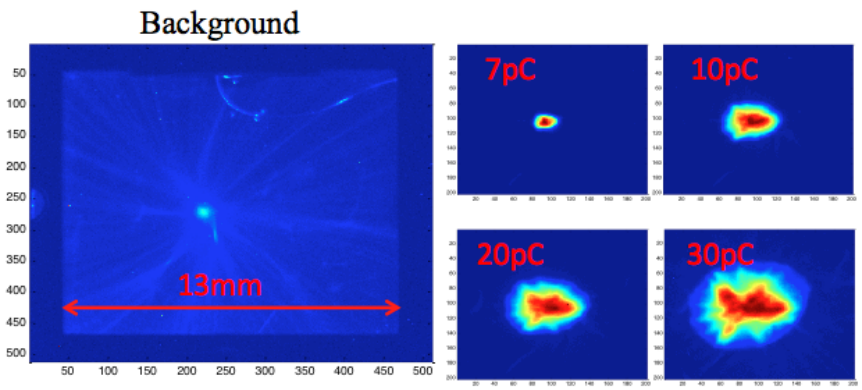


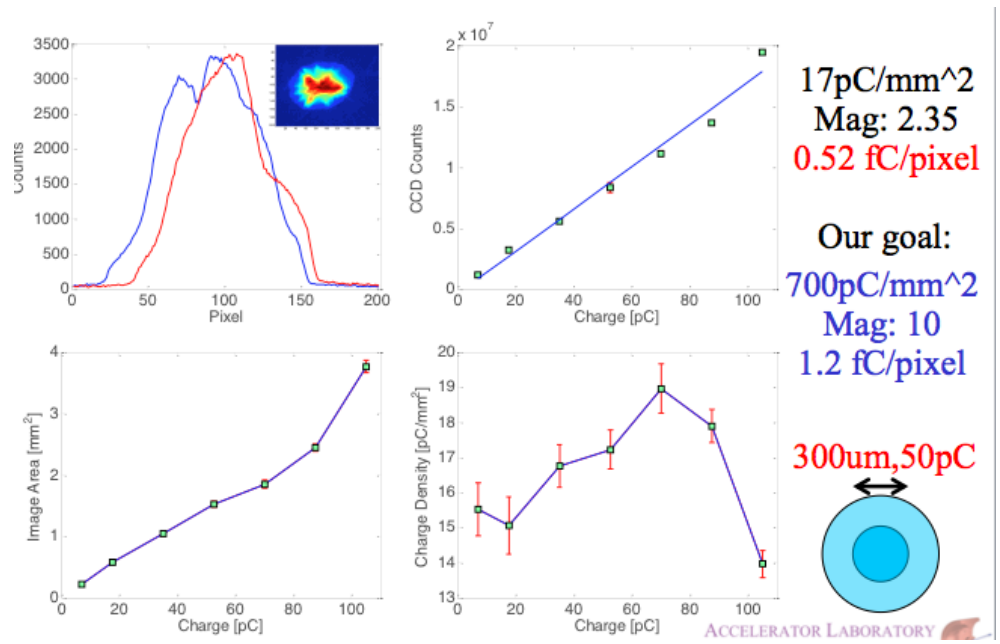
5um resolution can be achieved

Charge requirement test

- EMCCD needed.

Test using linac: 5 MeV
YAG:Ce screen: ~100 um
EMCCD: Andor 888, pixel size 13 um





The goal of Exp2

- To demonstrate the idea of transverse electron probe for CO2 LWFA snapshot

- To reconstruct the field structure of CO2 laser driven wake, and to compare with simulations.

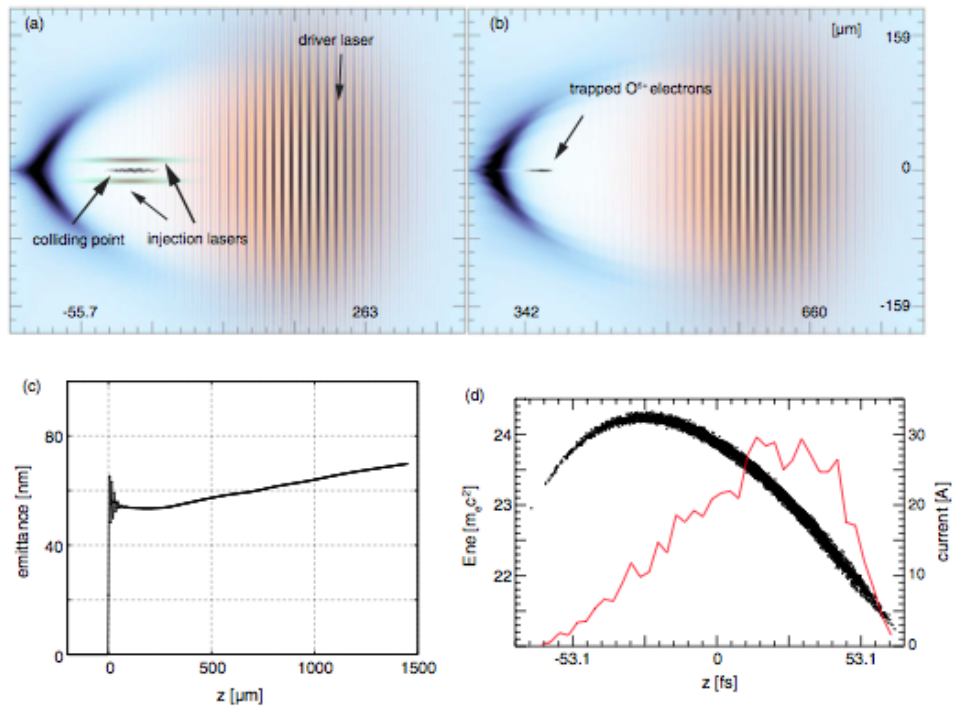
Exp3: Ionization Injection by Transverse Colliding Laser Pulses in High Power CO2 Laser Driven Wakes

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)



Yu et al., PRL 112, 125001 2014 (**co-linear two color**)
Xu et al., Phys. Rev. STAB 17,061301 2014 (**co-linear and transverse colliding two color**)

Key requirements

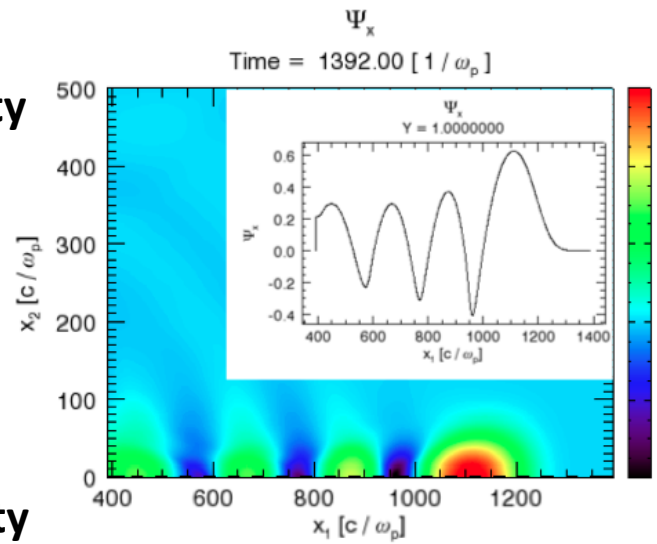
- 1ps 5TW is needed to drive a strong enough wake for ionization injection to occur

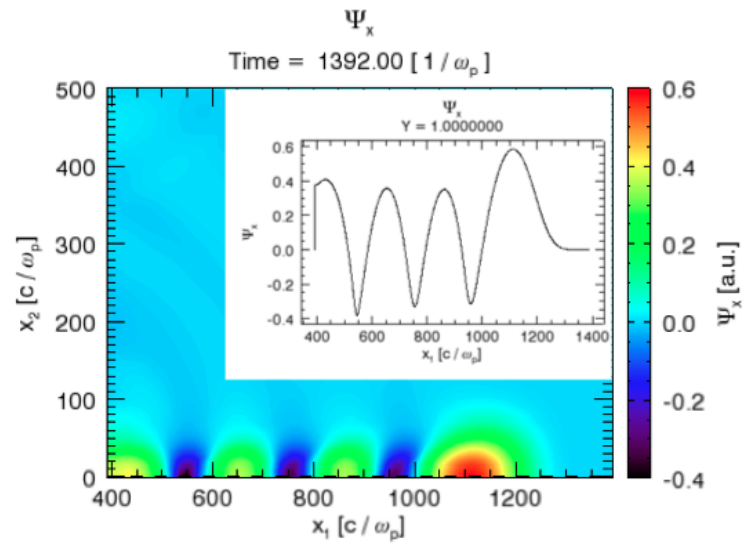
- The timing jitter between two lasers should be less than a few hundreds fs

1ps, 5TW, w0 = 70um, a0 = 2.162,
delta_psi=1.05

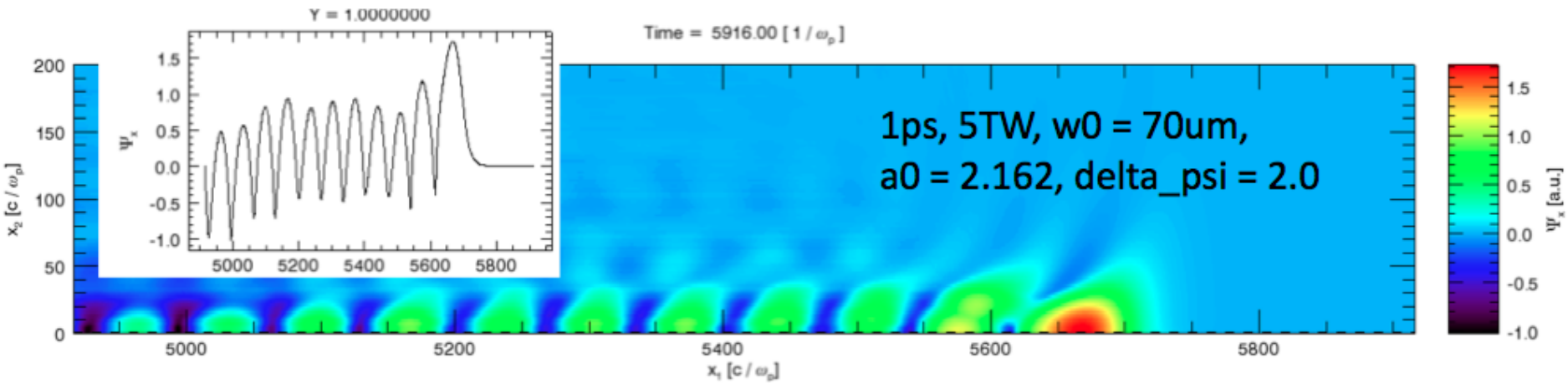
1ps, 5TW, w0 = 100um, a0 = 1.513,
delta_psi=0.93

Plasma density 10^16cm-3





Plasma density 10^17cm-3



Summary

- A strong CO2 driven LWFA program for key physics study can be readily started with current and near term laser and beam parameters at ATF
- Three experiments are proposed with reasonable feasibility, and the timeline for implementing all these experiments is about 1-3 years

Thank you for your attention!