AE99 progress report: Directional x-ray radiation produced by plasma magneto-static undulator

Yipeng Wu

Jan. 20, 2022

UCLA Team:

Chan Joshi (P.I.), Yipeng Wu, Chaojie Zhang, Mitchell Sinclair, Audrey Farrell, Zan Nie, Ken Marsh

ATF Team:

Igor Pogorelsky, Mikhail Fedurin, Karl Kusche, Rotem Kupfer, Misha Polyanskiy, Marcus Babzien , Paul Jacob, Mary Jane Ilardi and Mark Palmer

SBU Team:

Irina Petrushina, Navid Vafaei-Najafabadi

Currently supported by DOE-NNSA, DOE-HEP

UCLA

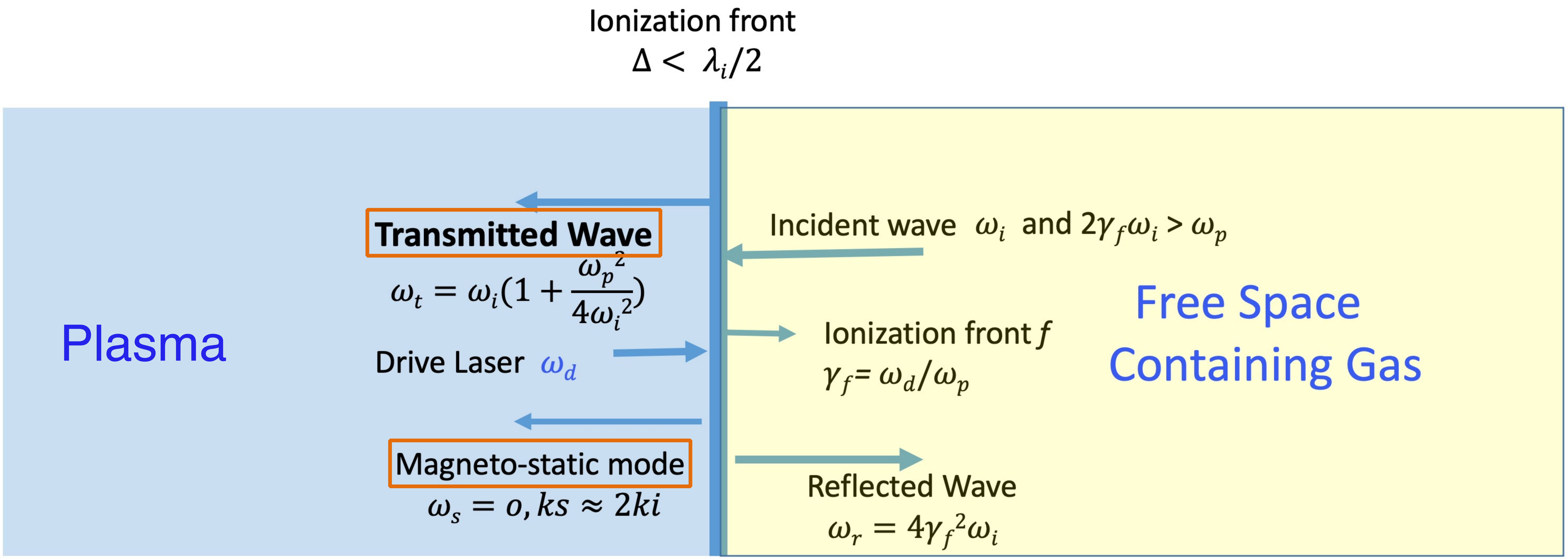
BROOKHAVEN NATIONAL LABORATORY

Accelerator Test Facility

Stony Brook University

What happens when e.m. wave is incident on a relativistic underdense plasma ionization front?

UCLA

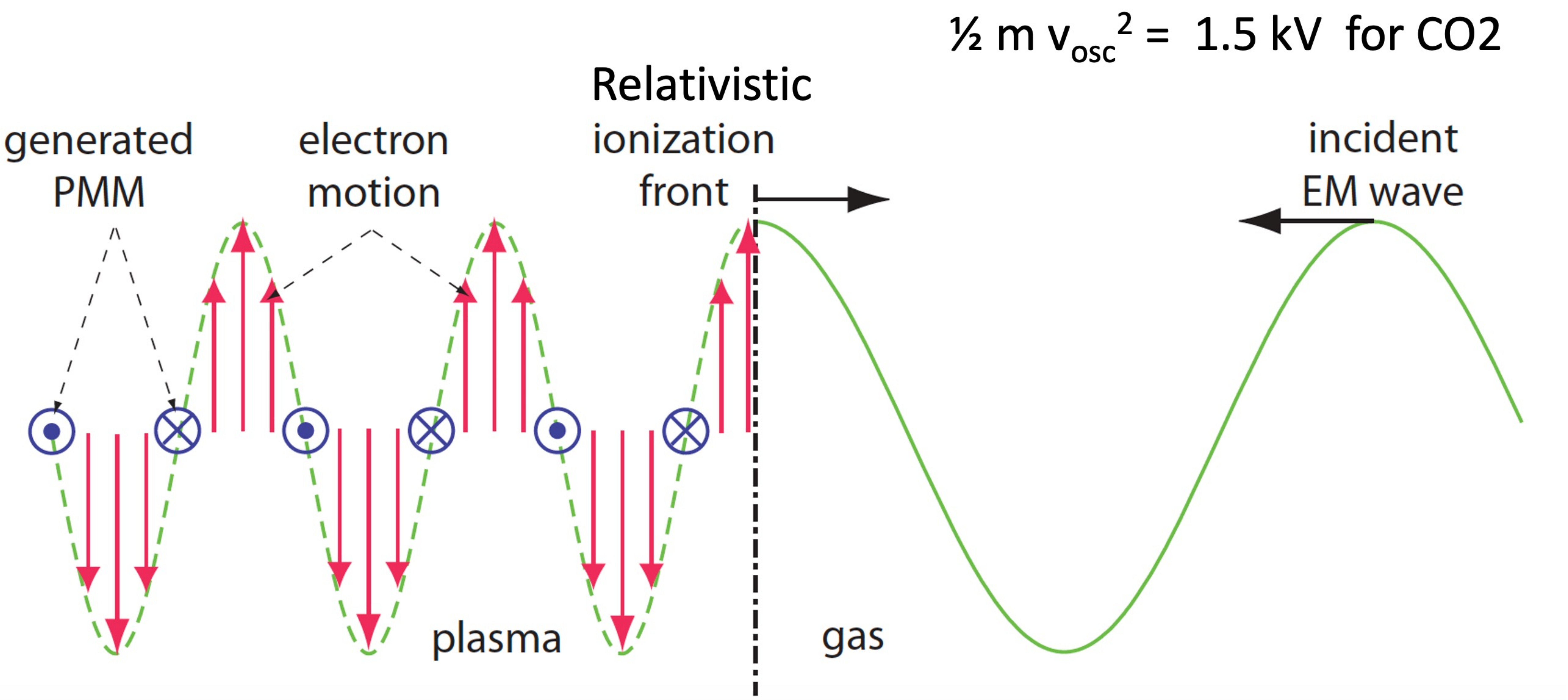


Boundary conditions at the ionization front are **E** and **B** must be continuous and **J=0** since electrons are born at rest
3 boundary conditions allows for 3 modes

Ref: F. Fiuza, L. Silva and C. Joshi PRSTAB 13(8):080701, Aug 2010

Observable 1: Magneto-static (MS) mode

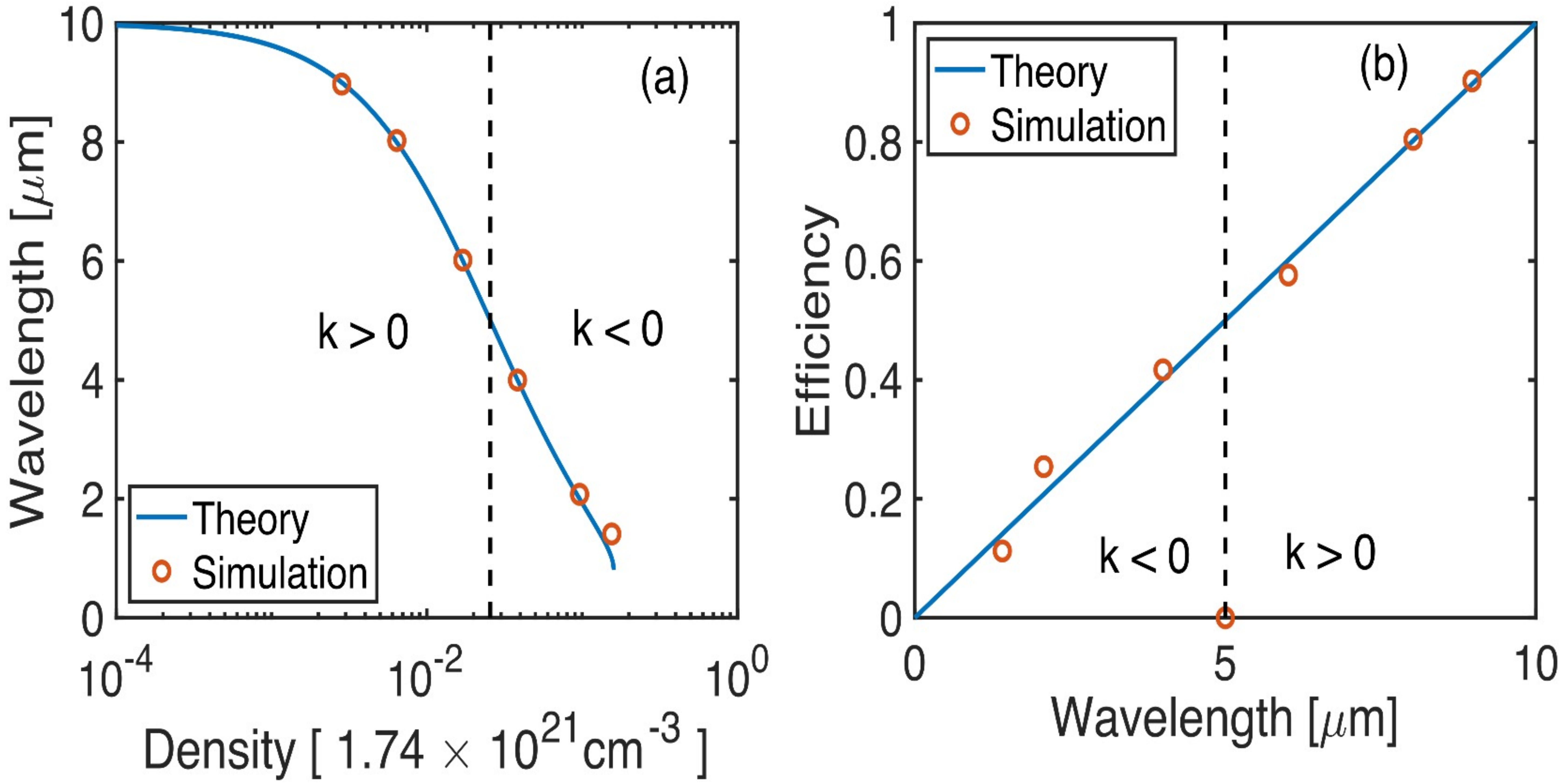
W.B. Mori, **Phys**. **Rev**. A **44**, **5118** (**1991**)



Ionization front must be narrower than ½ wavelength of CO_2 radiation

Observable 2: Frequency upshifted e.m. waves

UCLA



(a) Output wavelength vs ionization front density. (b) Energy conversion efficiency vs output wavelength.

For 10.6 um incident

Up to density of $4\text{x}10^{19}$ cm-3
The upshifted wave is transmitted

Beyond this density the wavenumber of the wave becomes negative

The upshifted wave therefore Is now reflected.

Zan Nie, Yipeng Wu, et al., Phys. Plasmas 28, 023106 (2021)

Experimental goal

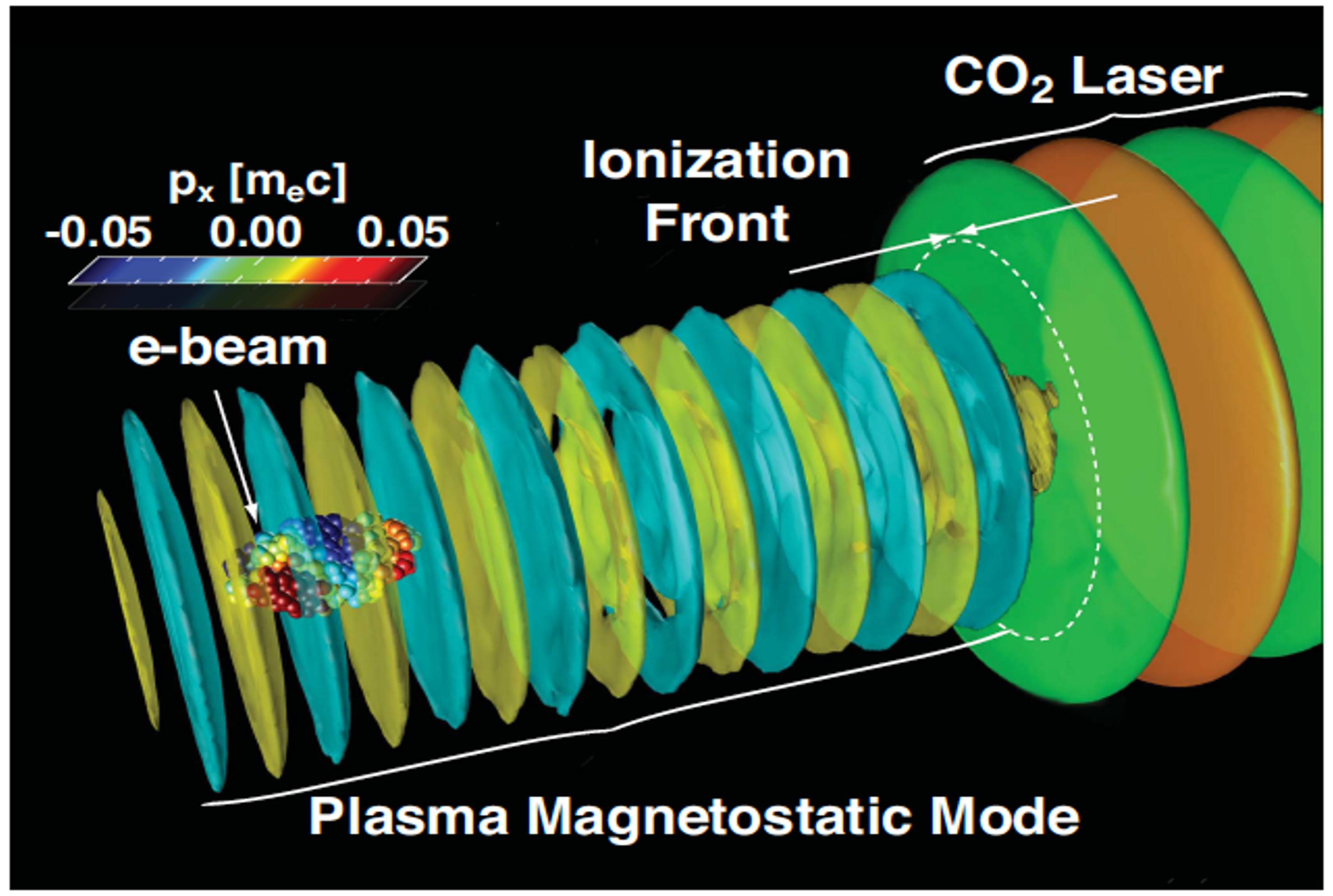
UCLA

1. Year 2021+2022

- Demonstrate the excitation of MS mode through the collision of relativistic ionization front with CO2 laser pulse by measuring:
  - magnetic field using electron probe with permanent magnet quadrupoles (PMQ) imaging system
  - frequency upshifted radiation using IR spectrometer

2. Final goal

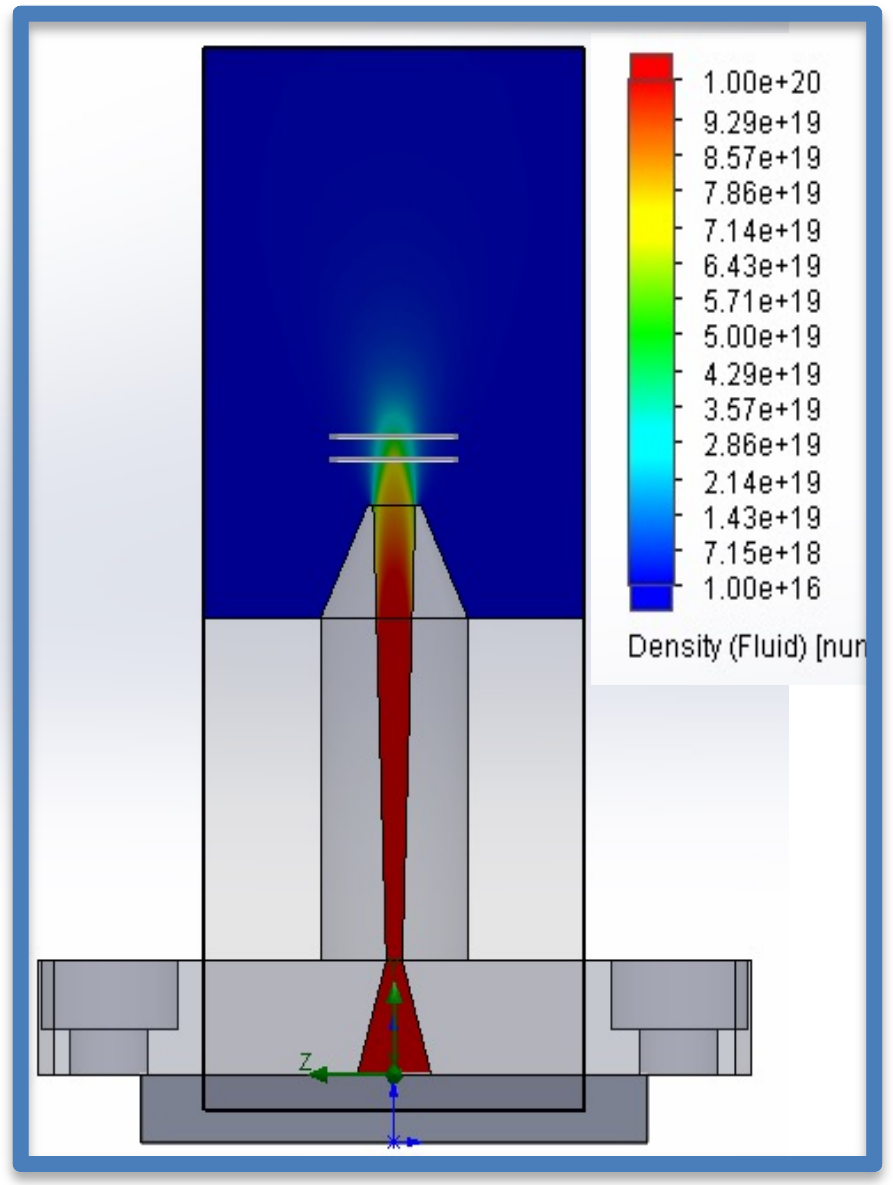
- Demonstrate X-ray radiation generation through an electron beam propagating through the MS mode



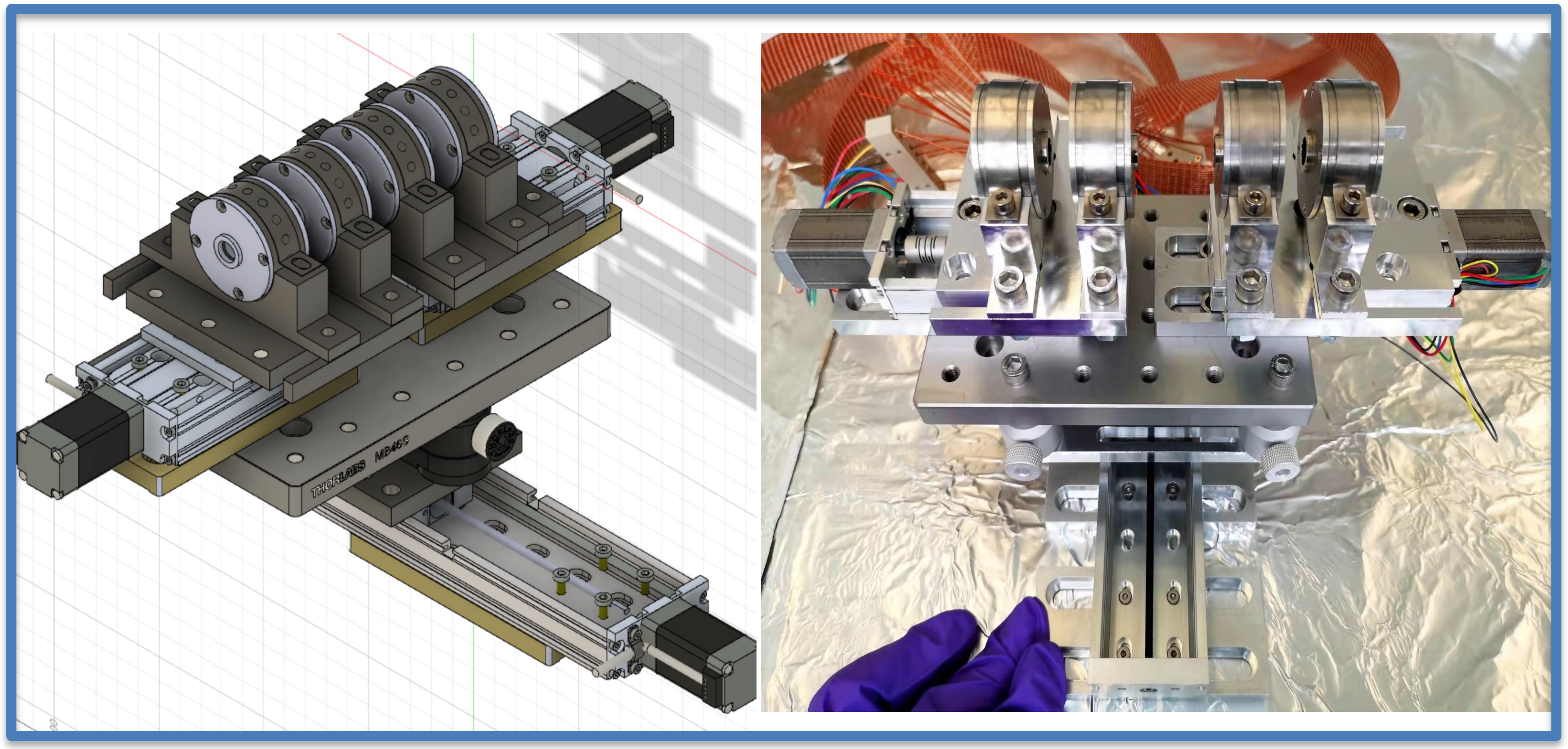
Experimental campaign for Year 2021

UCLA

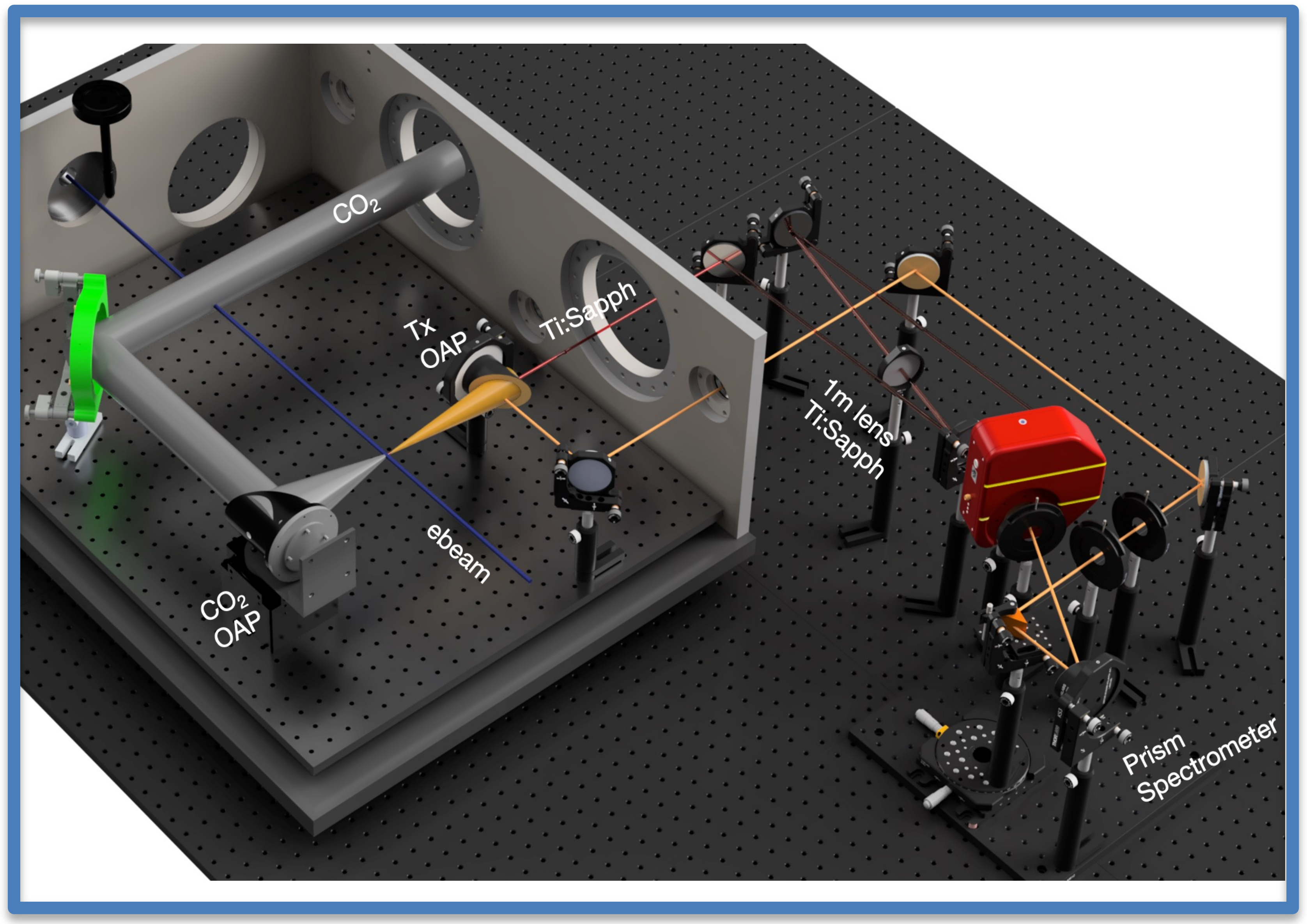
1. Developed the gas jet, e-probe imaging system with PMQ and IR spectrometer at UCLA
2. In July-August, we set up the AE99 experiment at ATF and tested almost all the techniques and diagnostics
3. We obtained preliminary results and developed a better understanding of how to improve the AE99 experiment in the future



Gas jet



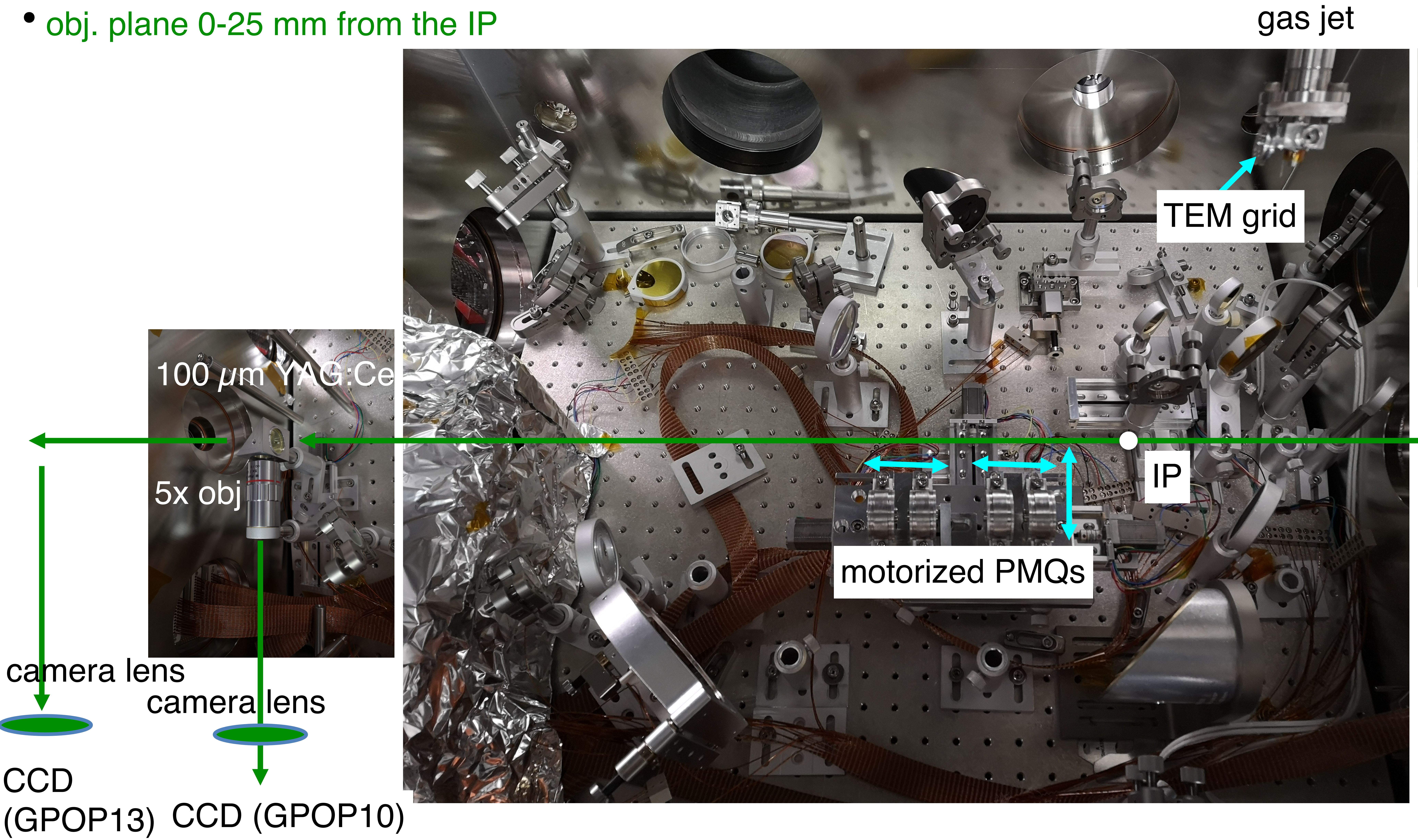
PMQ

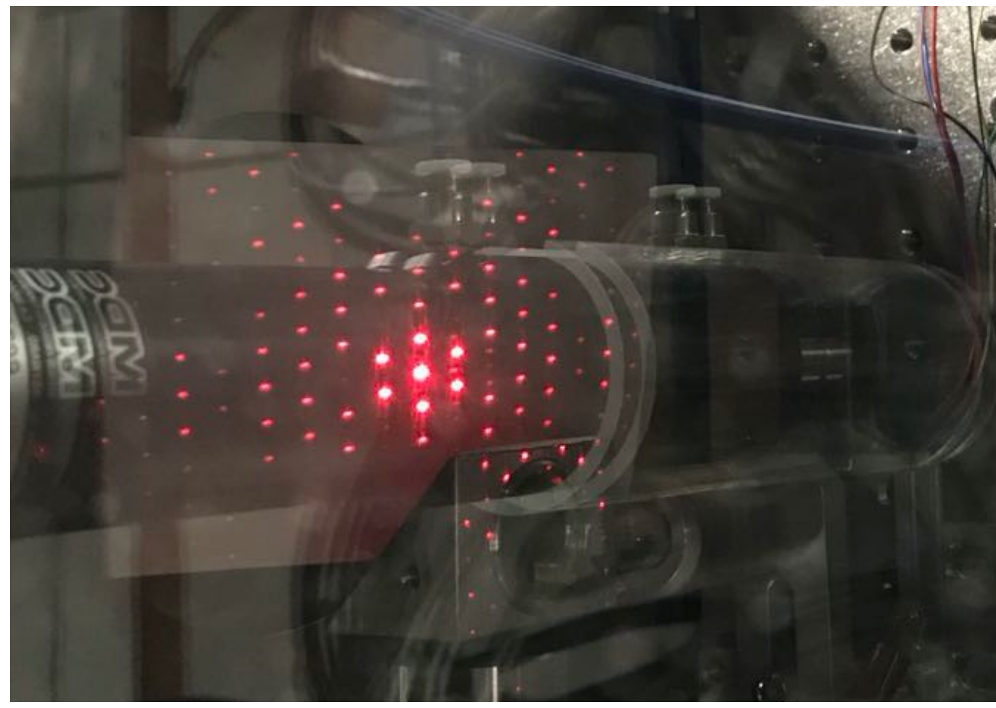


IR spectrometer

Experimental layout (PMQ test)

- obj. plane 0-25 mm from the IP

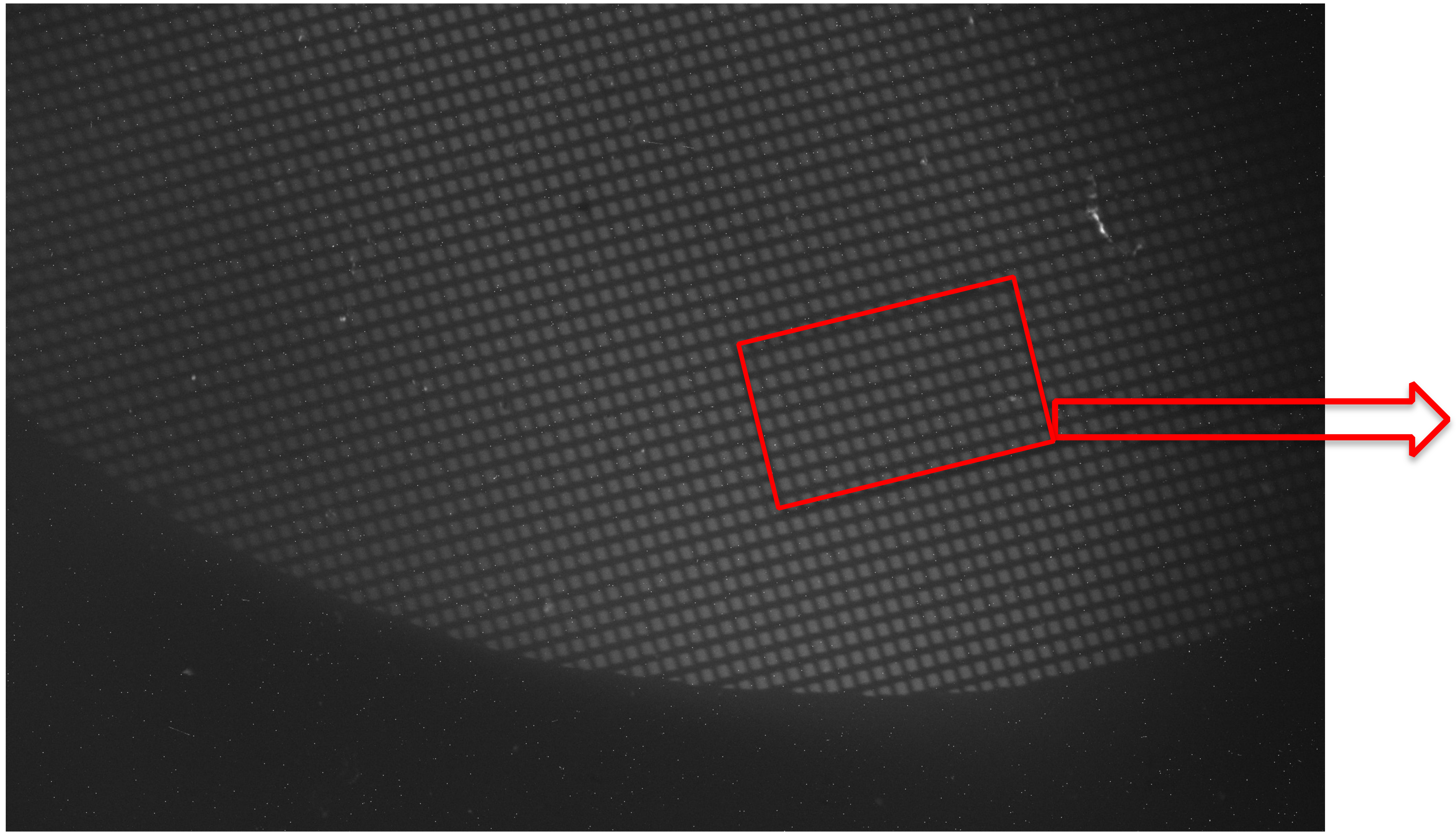


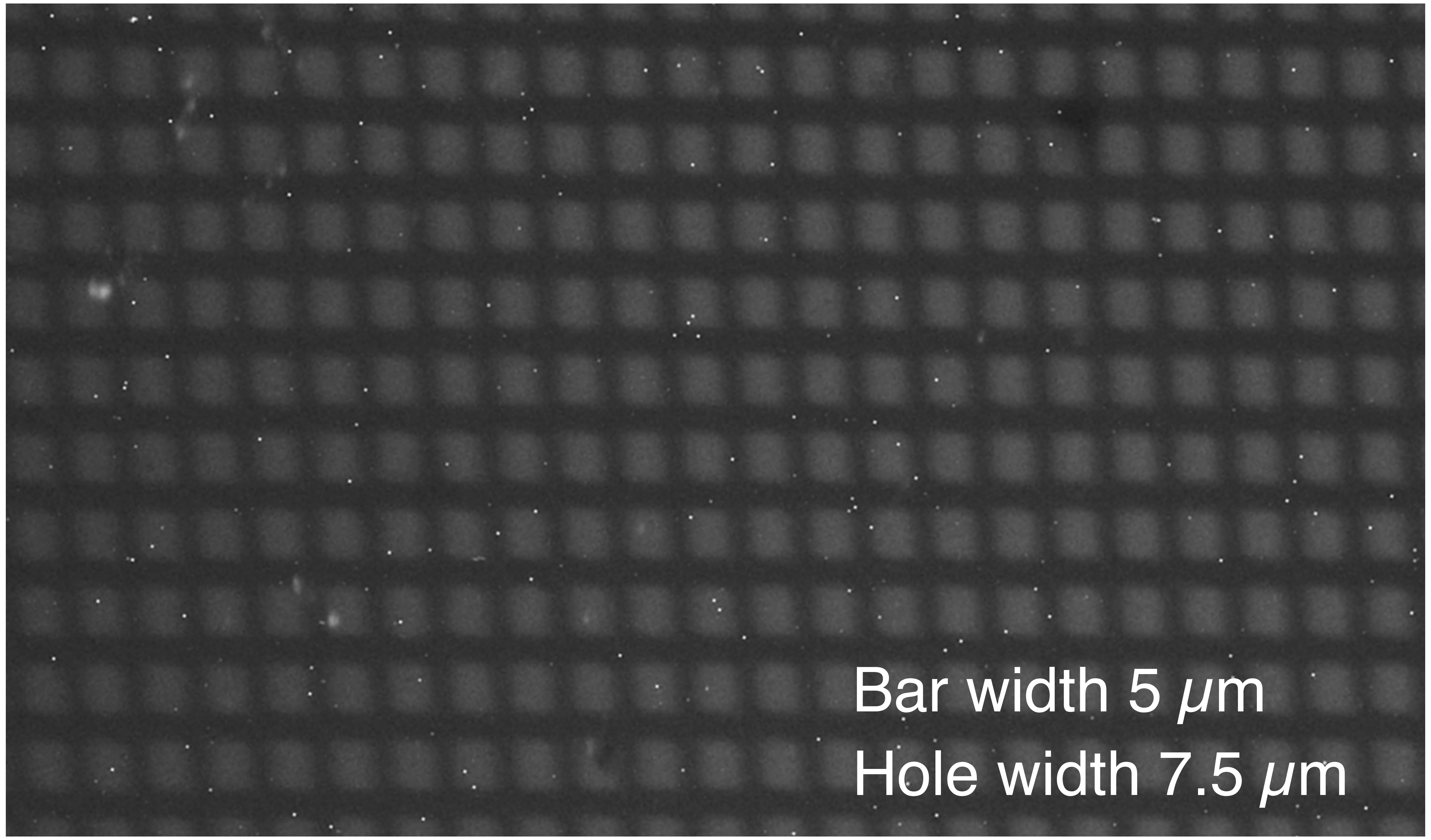


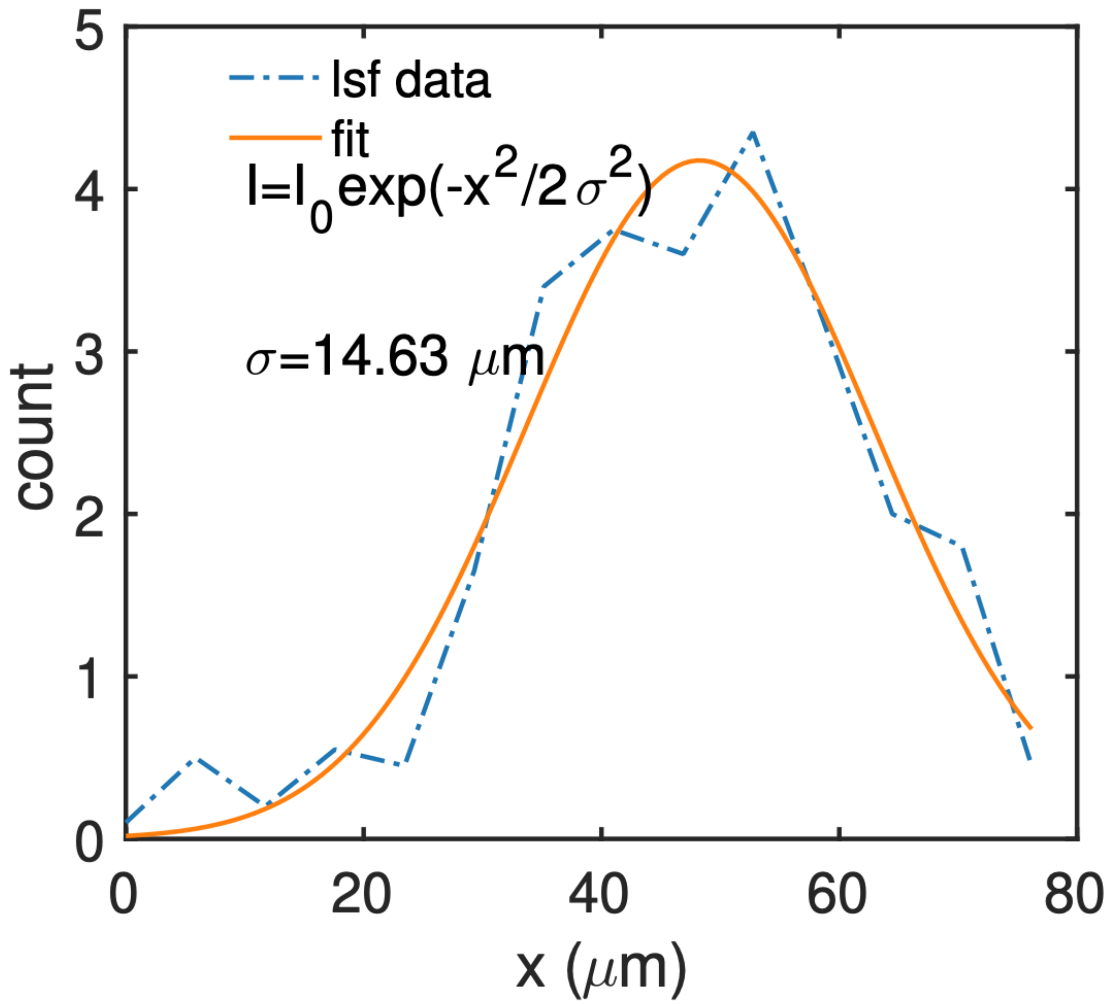
TEM grid aligned using beamline HeNe

~2.8μm resolving power measured using the 2000-mesh TEM grid at GPOP10

UCLA







σ=14.63/12.37≈1.2 μm

Resolving power: ~2.8 μm

B field wavelength: 4.6 μm

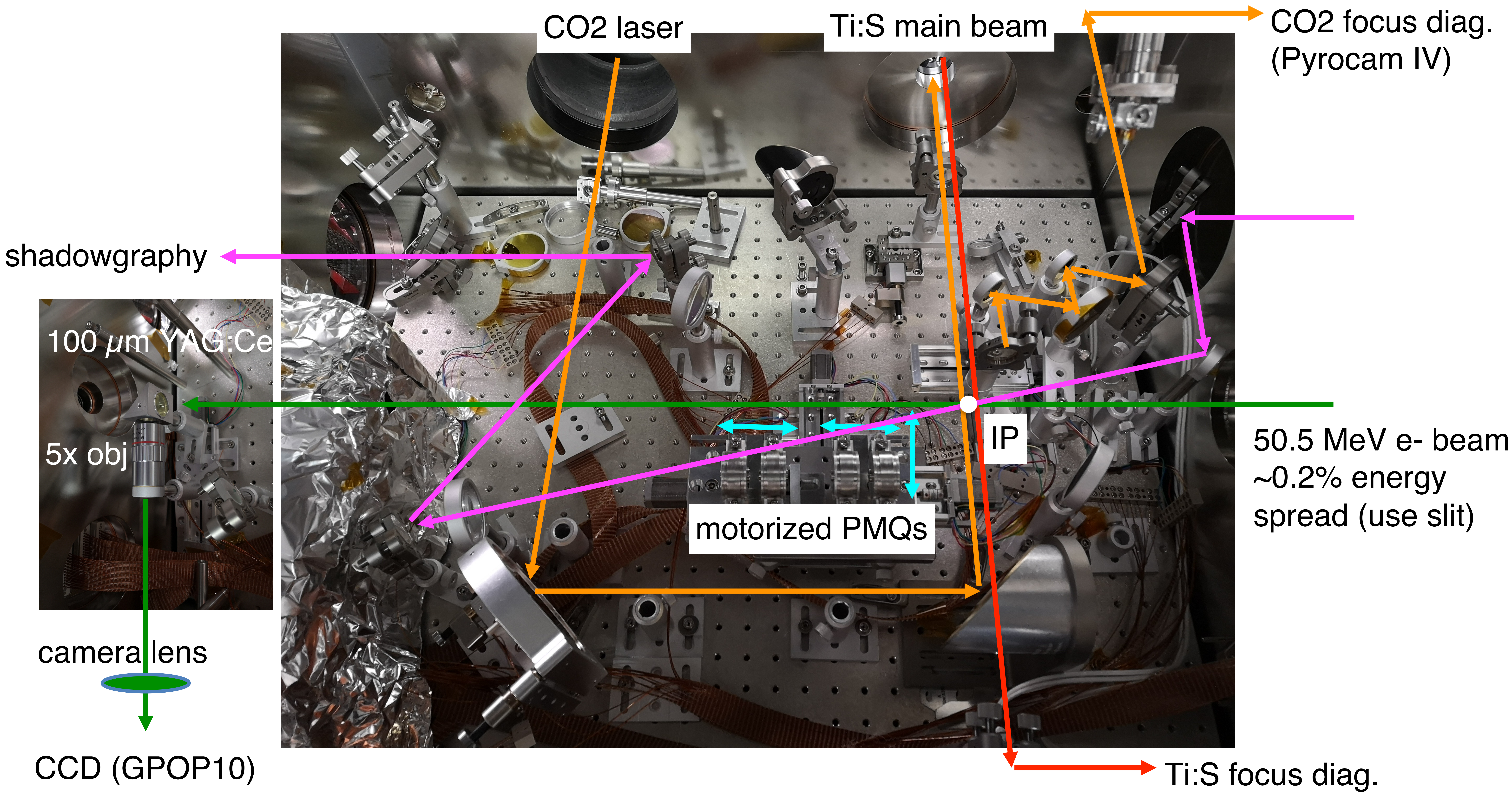
Overall magnification (e- beam + optical): ~12.4x

Optical magnification: 3.34x

PMQ e- beam magnification: 3.7x (design ~3.8x)

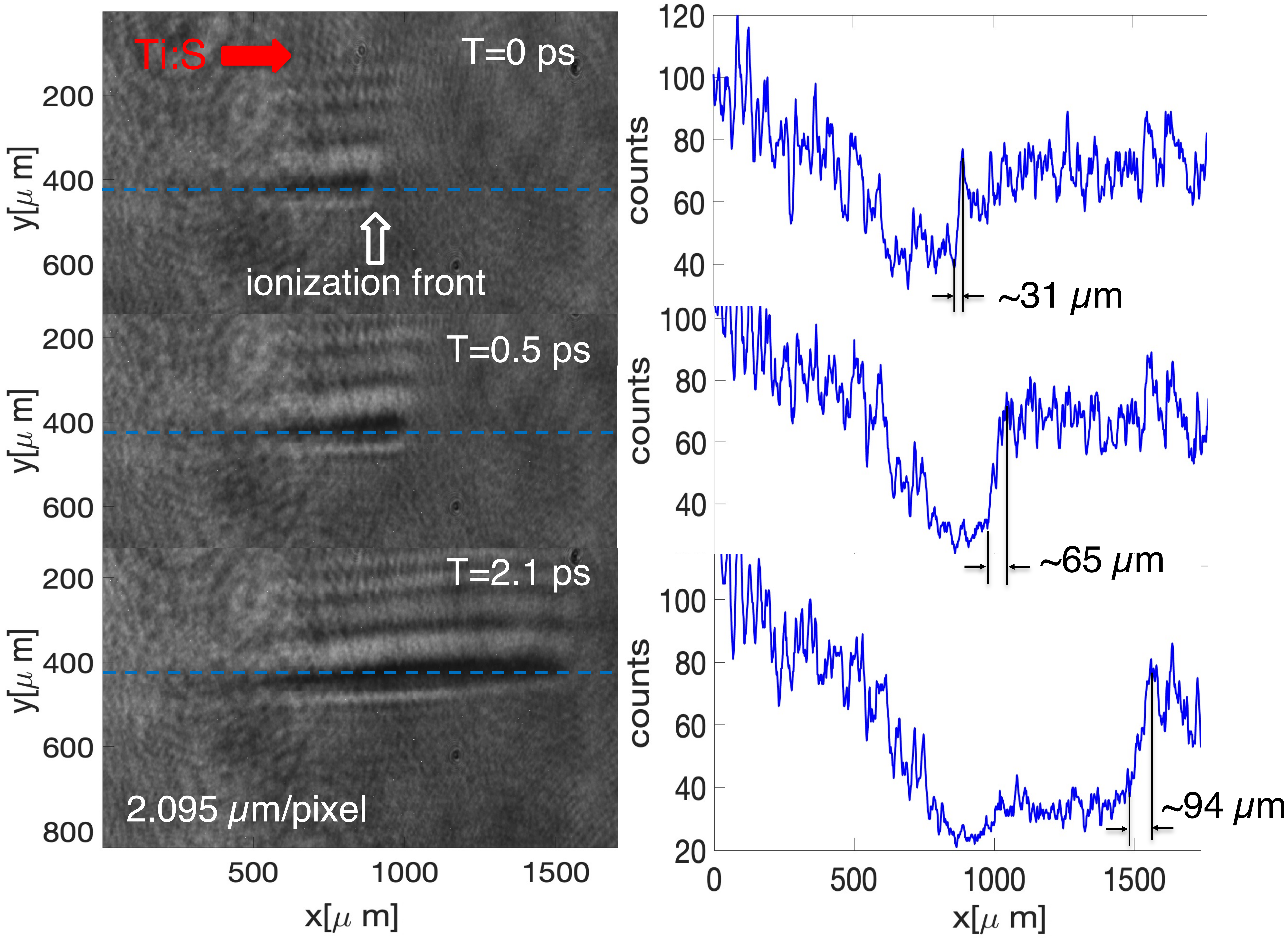
Experimental layout (AE99 e- probe)

UCLA



Ionization front measured using optical shadowgraph

UCLA



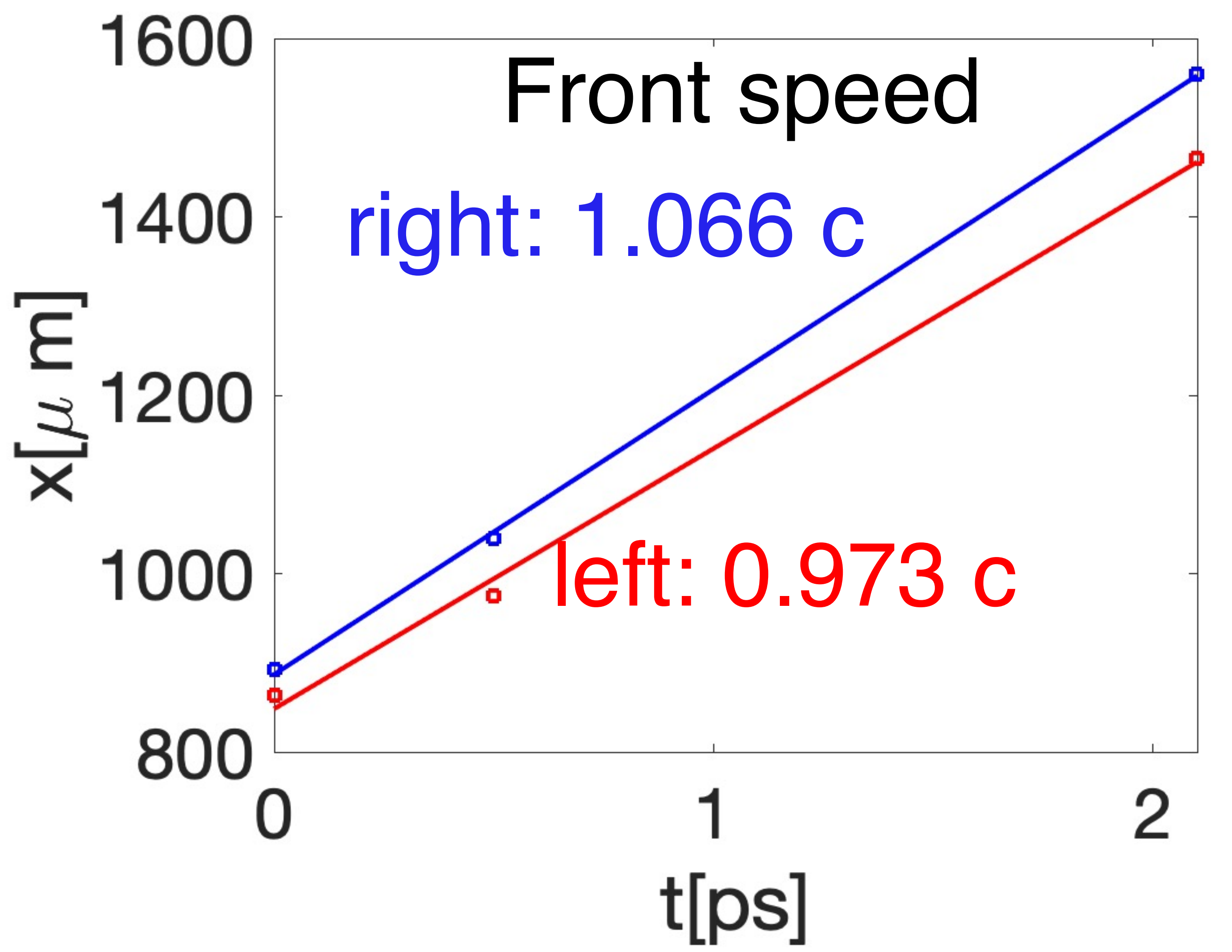
- ✓ Excite an ionization front over 2 ps (600 μm, 120 periods of B field)
- ✓ Ionization front width > 30 μm, larger than ½ CO_2 wavelength

Associated Ti:S Laser Parameters

- Pulse length >70 fs
- Energy: ~4 mJ on target
- Focal spot size ~50 μm
- Focal quality not good due to aberration and maybe spatial chirp

Desired Upgrades to Ti:S

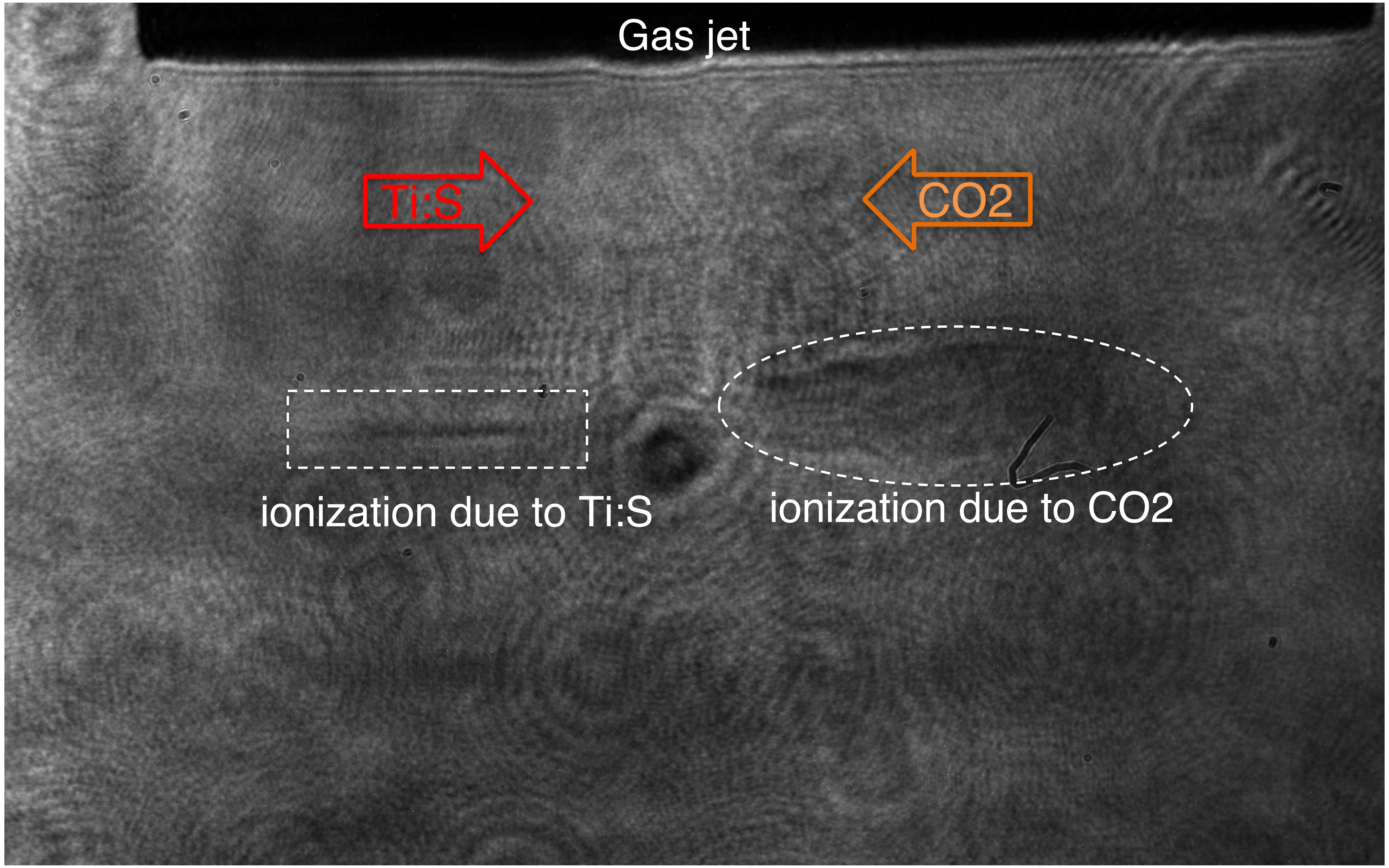
- Higher deliverable energy
- Improved phase front
- Decreased pulse length



Synchronization and overlapping

UCLA

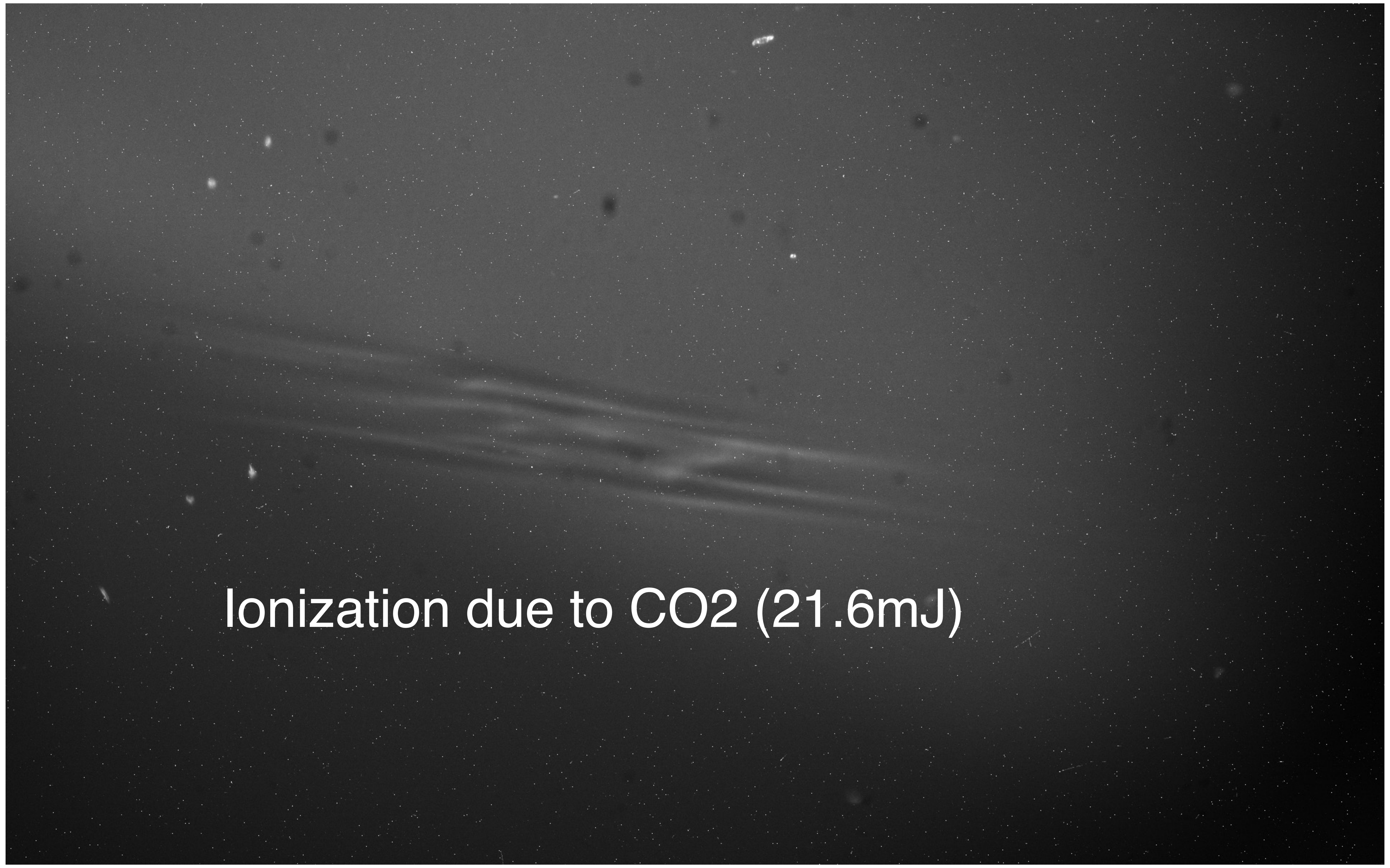
- Synchronization of Ti:S and CO2 is done using the optical shadowgraph (relatively large jitter ~10ps)
- Synchronization of e-beam and CO2 is done using the electron imaging method
- Spatial overlapping of Ti:S and CO2 is done using the optical shadowgraph (vertical direction) and a needle tip (within 100 μm)

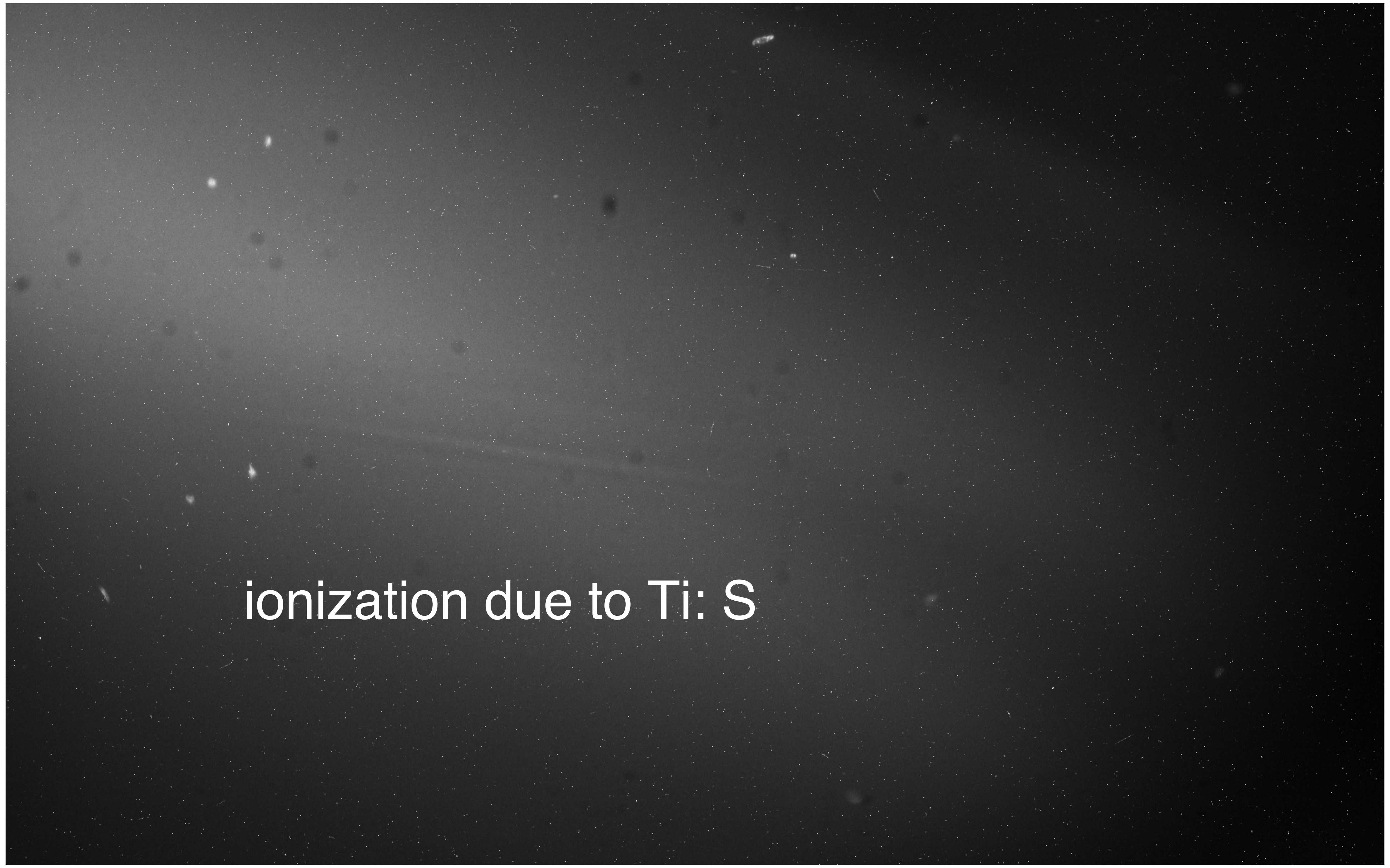


Experimental data using PMQ (ionization of CO_2 and Ti:S)

UCLA

The PMQ e-beam imaging system can probe the ionization line very well!



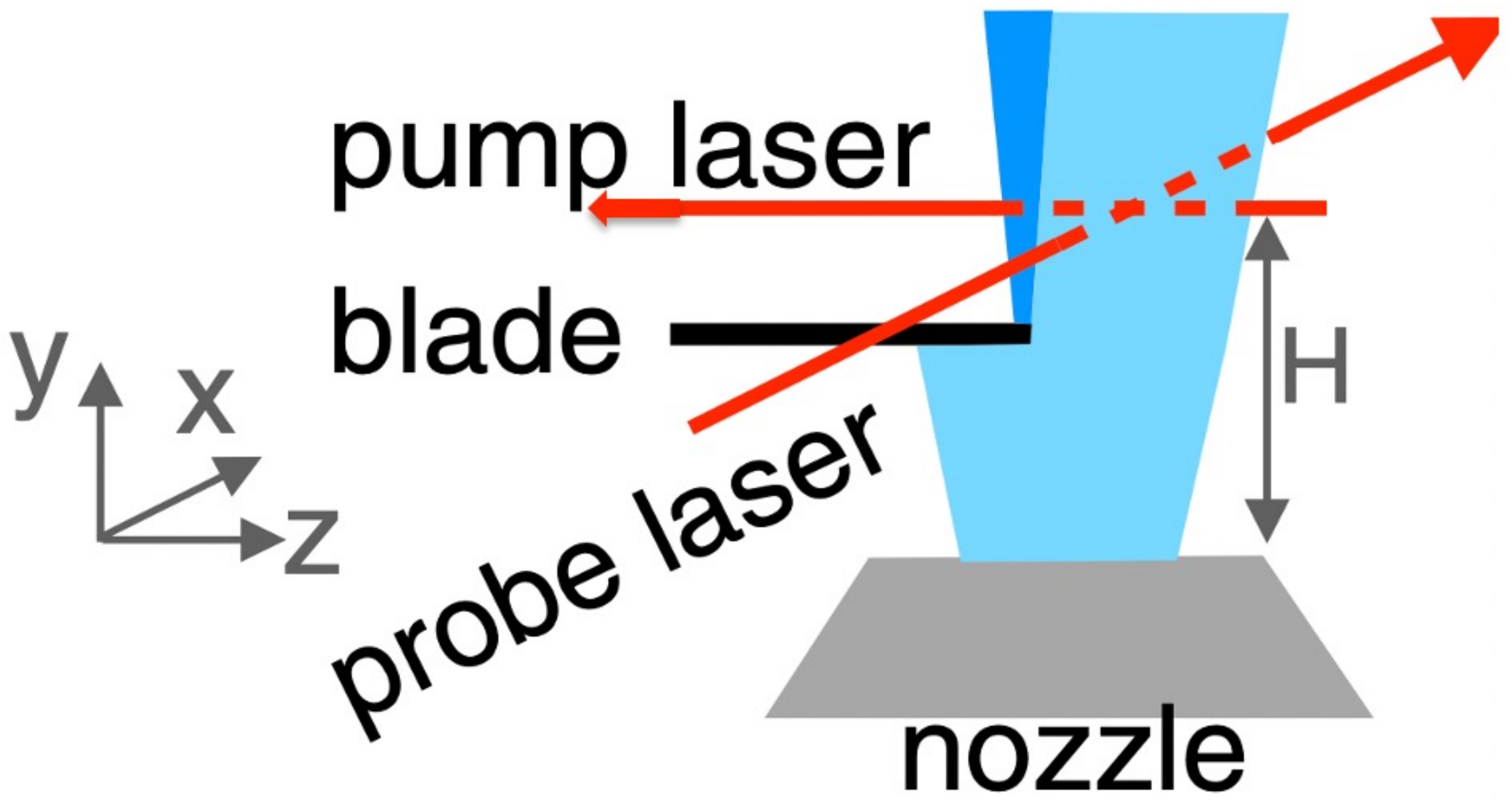


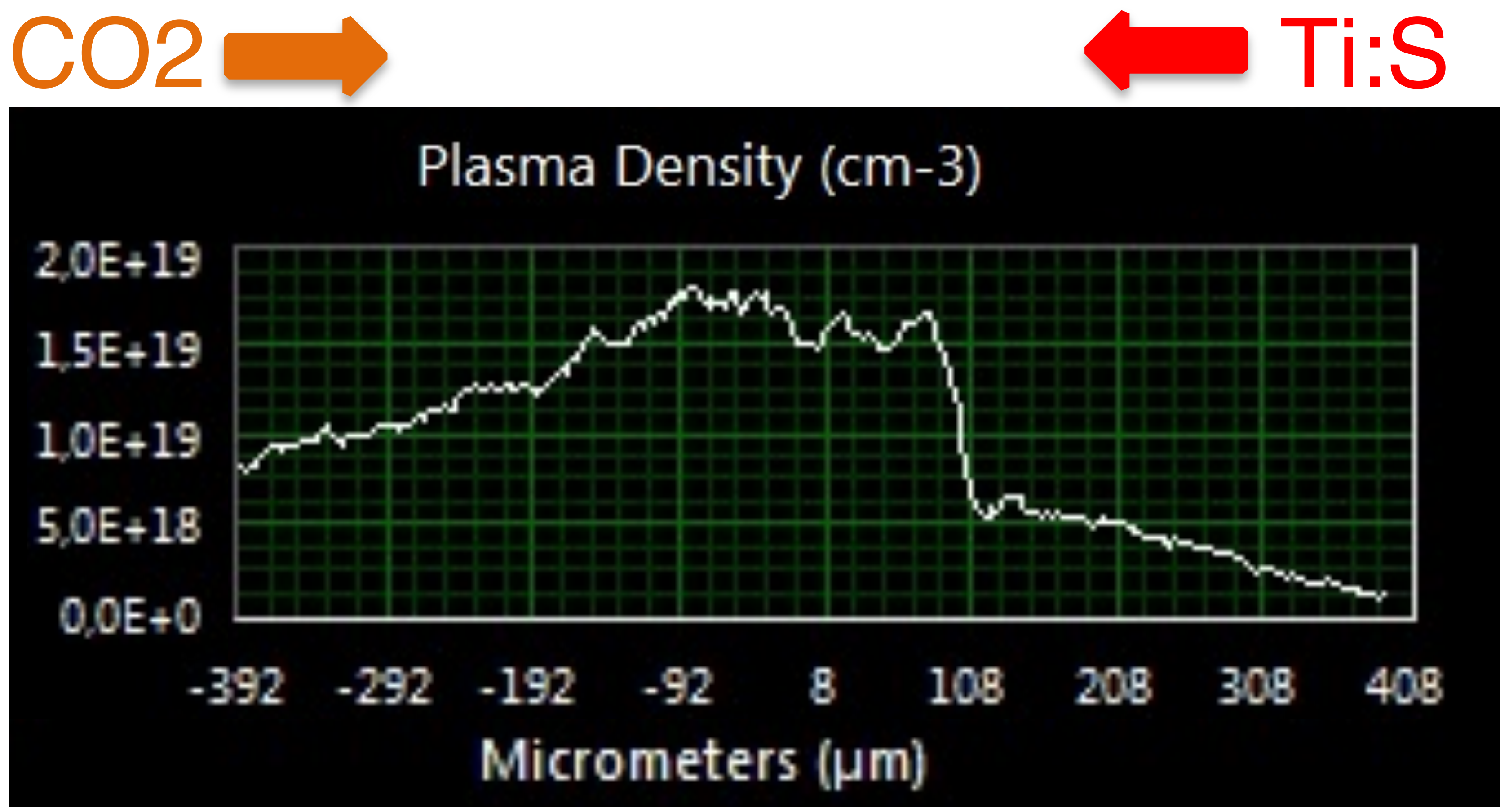
- With the last amplifier of CO_2, the energy (21.6mJ) is high to ionize the gas (left figure);
- Without the last amplifier of CO_2, the energy is low, unable to ionize the gas (right figure)

Plan for Year 2022

Continue the AE99 experiment by measuring MS B fields and upshifted radiation with improved parameters (shorter ionization front, higher plasma density…) and better diagnostics

- **Improvements at UCLA:**
  - Increase the plasma density from ~10^{18} cm^{-3} (2021 run) to ~10^{19} cm^{-3}
    - ➢ a shorter gas jet
    - ➢ Inserting a blade to create a shock
  - PMQ imaging system improvement
    - ➢ increase the measurement range of B field: adding another moving stage to increase the distance from IP to PMQ
    - ➢ further improve the resolution power: using a 10x objective for GPOP10 and using a EMCCD camera
  - Use an OAP to focus the Ti:S laser: higher power and reduced aberration





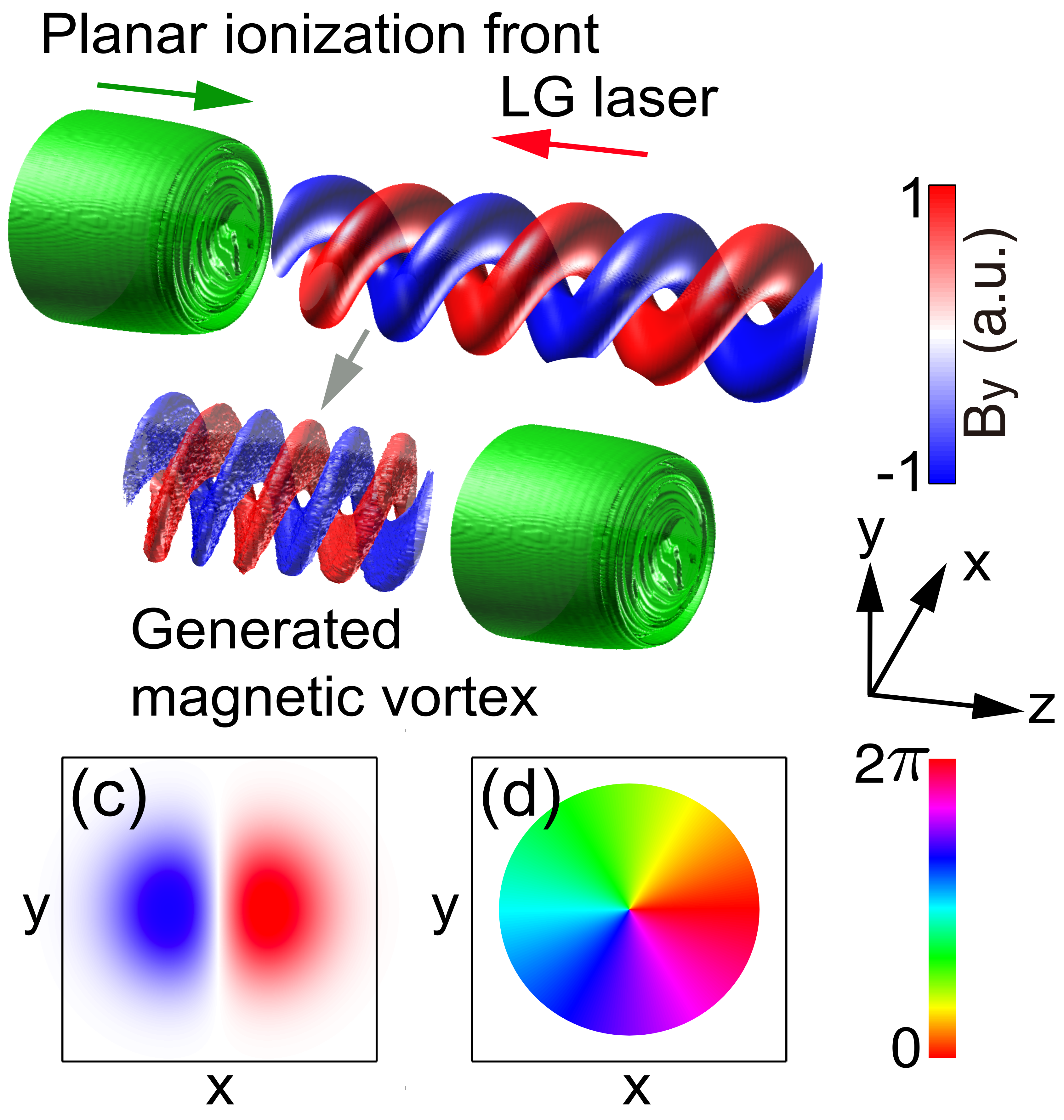
Plan for Year 2022

- **Desired ATF facility upgrade:**
  - Upgrade of the Ti:S system
  - ➢ higher deliverable energy: vacuum transport
  - ➢ decreased pulse length: compression optimization
  - ➢ reduced pulse shoulder
  - ➢ improved phase front
  - ➢ single-shot mode (need a shutter)
  - ➢ improve the synchronization of Ti:S with CO2/e-beam (~10ps jitter is relatively large)
  - Gas-jet motorized in the vertical direction (currently is only motorized in the horizontal plane)

- **Time:** (4-5 weeks during May to June, combined with AE98 if possible)

Future plans

- Generation of circularly polarized MS B fields by using a circularly polarized CO_2 laser
- Generation of magnetic vortex by using a Laguerre-Gaussian CO_2 laser



Summary of products delivered from the work to date

UCLA

- First experimental campaign: 7/19/2021 — 8/20/2021 (AE98+99)

- **Conference**
  - Two talks at the 63rd APS-DPP meeting (Yipeng + Mitchell)

- **Papers**
  - Ultra-short pulse generation from mid-IR to THz range using plasma wakes and relativistic ionization fronts, ***invited paper***, Phys. Plasmas 28, 023106 (2021)
  - Generation of strong magnetic vortices and tunable optical vortices in plasmas, in preparation

Electron beam requirements

UCLA

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	***50.5 MeV***
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	***<0.1 for best compression***
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	***<1 ps***
Transverse size at IP (σ)	µm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	***>1 mm (horizontal) >0.5 mm (vertical)***
Normalized Emittance	µm	1 (at 0.3 nC)	*Variable with bunch charge*	***<1 mm mrad***
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	***1.5 Hz***
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	***single bunch***

CO_2 laser requirements

UCLA

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	***9.2 µm***
	Peak Power	GW	~3		***3***
	Pulse Mode	---	Single		***single***
	Pulse Length	ps	2		***2***
	Pulse Energy	mJ	6		***6***
	M^2	---	~1.5		***OK***
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	***OK***
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	***linear***
CO_2 CPA Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	***9.2 µm***
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	2	*~5 TW operation is planned for FY21 (requires further in-vacuum transport upgrade). A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	***<0.1***
	Pulse Mode	---	Single		***single***
	Pulse Length	ps	2		***2***
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available in FY20*	***<0.1***
	M^2	---	~2		***OK***
	Repetition Rate	Hz	0.05		***OK***
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	***Linear***

Other Experimental Laser Requirements

UCLA

Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments	Requested Values
Central Wavelength	nm	800	800	*Stage I parameters have been delivered, while Stage II parameters will be available for user experiments once our vacuum transport installation is complete (now planned for FY21 after COVID-19 delays)*	***800 nm***
FWHM Bandwidth	nm	20	13		***OK***
Compressed FWHM Pulse Width	fs	<55	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.*	***OK***
Chirped FWHM Pulse Width	ps	≥50	≥50		***OK***
Chirped Energy	mJ	>30	200		***OK***
Compressed Energy	mJ	>14	100		***OK***
Energy to Experiments	mJ	>10	>80		***>20***
Power to Experiments	GW	>250	>1067		***OK***

Nd:YAG Laser System	Units	Typical Values	2021 Modifications	Comments	Requested Values
Wavelength	nm	1064	1064	*Single pulse*	
Energy	mJ	5	100		
Pulse Width	ps	14	<20		
Wavelength	nm	532		*Frequency doubled*	
Energy	mJ	0.5			
Pulse Width	ps	10			

Special Equipment Requirements and Hazards

UCLA

- **Electron beam**
  - same as AE93 and AE98
- **CO_2 laser**
  - same as the parameters used in Year 2021
- **Ti:Sapphire laser**
  - improved power, pulse length, beam quality and pointing stability
- **Hazards and special Installation Requirements**
  - none

Experimental Time Request

UCLA

CY2022 Time Request (combined with AE98 if possible)

Capability	Setup Hours	Running Hours
Electron Beam Only	***16***	***24***
Laser* Only (in Laser Rooms)	***currently unknown***	***currently unknown***
Laser(s)* + Electron Beam	***24***	***40***

Time Estimate for Remaining Years of Experiment (including FY2022)

Capability	Setup Hours	Running Hours
Electron Beam Only	***48***	***64***
Laser* Only (in FEL Room)		
Laser(s)* + Electron Beam	***32***	***160***

Thank you for your attention

We want to thank the ATF BNL team for their support.

Backup slides

Ti:S laser focused by a lens of f=250 mm (lens perpendicular to the laser)

UCLA

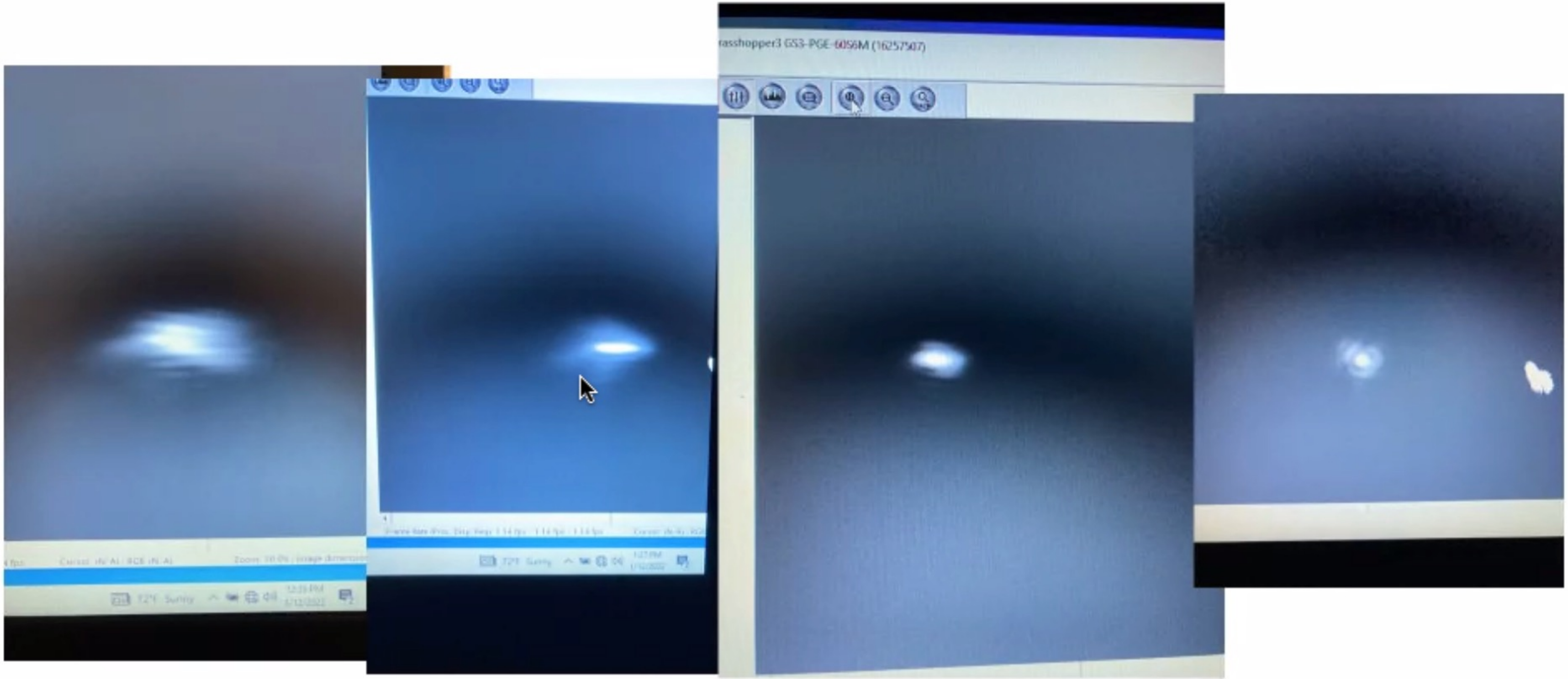
Spot size: ~52.7 μm FWHM

If the lens is perpendicular to the laser: relatively large aberration.

If the lens is tilted to partially compensate for the aberration, the laser spot at focus is not round (the horizontal size is ~3 times of the vertical size). Maybe it was due to the spatial chirp.

Correcting spatial chirp at UCLA

UCLA



ATF pre-pulse or pulse shoulder

UCLA