AE-95 Report: Optical diagnosis of Self-Modulated CO2-laser driven plasma wakes

R. Zgadzaj, Yuxuan Cao, James R Welch, **M. C. Downer** - *University of Texas at Austin*

I. Petrushina, A. Jain, A. Gaikwad, A. Cheng, L. D. Pinto de Almeida Amorim, M. Flament, P. Iapozzuto, Y. Jing, J. Yan, S. Kongtawong, P. Kumar, **R. Samulyak**, **N. Vafaei-Najafabadi**, **V. Litvinenko** - *Stony Brook University*

C. Zhang, W.B. Mori, C. Joshi -
University of California Los Angeles

M. Babzien, M. Fedurin, P. Kaur, R. Kupfer, K.Kusche, M. Polyanskiy, C. Swinson, **I. Pogorelsky**, M. Palmer - *Brookhaven National Lab, Accelerator Test Facility*

This work is supported by U. S. DoE grants:
DE-SC0014043, DE-SC0011617, and DE-SC0012704.

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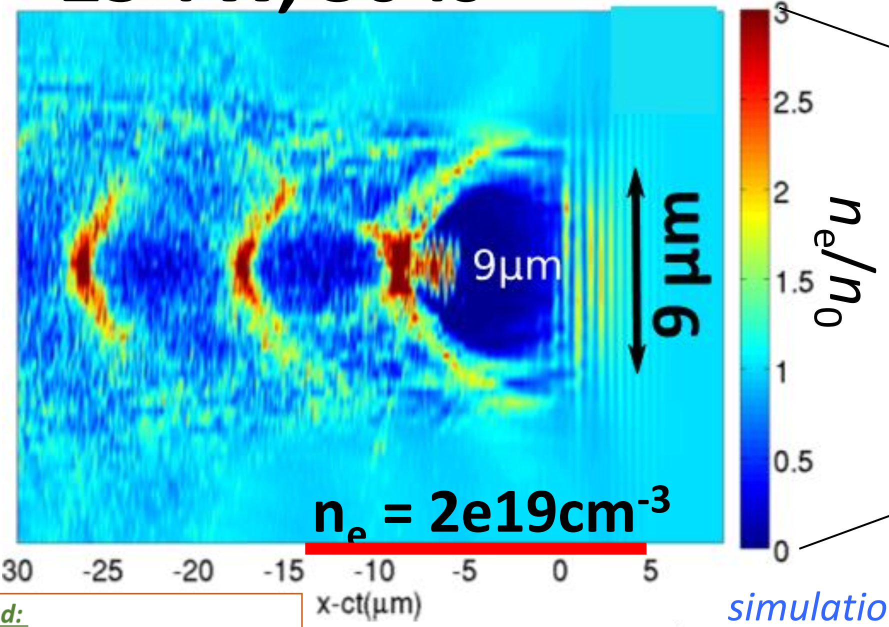
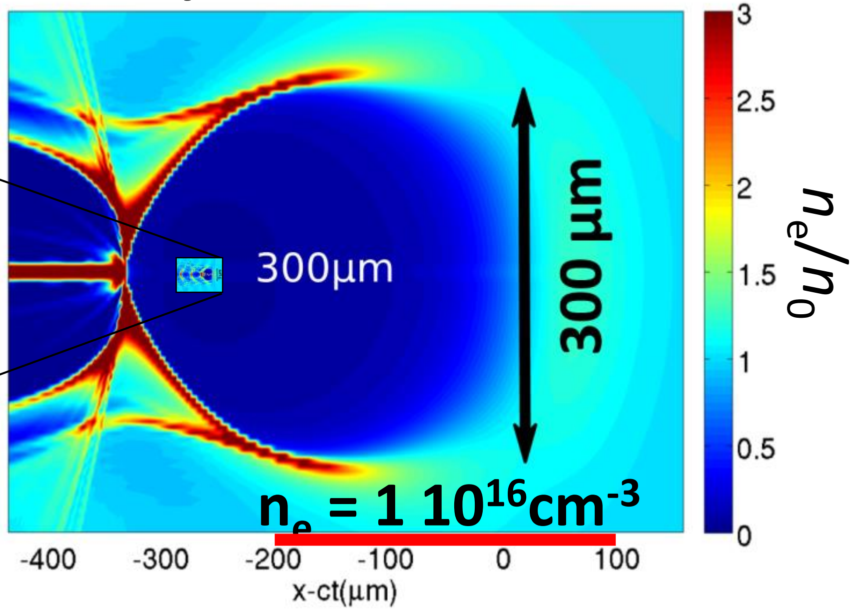
Vision: ~~Quasi-~~mono-energetic LWFAs based on large, controlled mid-IR laser-driven bubbles

injection with ΔE/E ~ 0.1% from external linac or µm-focused ionizing laser

λ_{drive}= 0.8 µm (UT)
25 TW, 30 fs

λ_{drive}= 10 µm
25 TW, 500fs





simulations courtesy G. Shvets

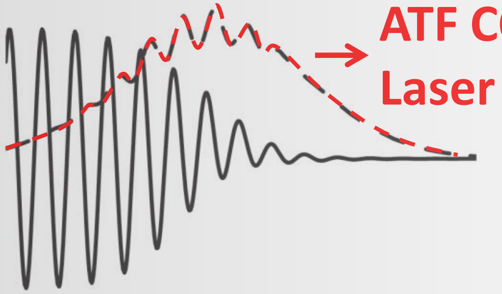
<u>Large blowout region</u>

Already in hand:
- **10 fs bunch duration:** high peak current at IP, minimize beamstrahlung

Unsolved problems:
- **0.1% energy spread:** observation of resonant particle creation processes.
- **high spin-polarization:** detection of parity-violating interactions, nuclear spin
- **nC charge**: high luminosity at IP.
- **staging:** easier with large LWFAs..

Precise and controllable *injection* from ATF Linac (or laser ionization AE88)
Detailed *optical visualization* of plasma wave density structure AE95
Detailed *radiographic visualization* of plasma wave E-field AE93

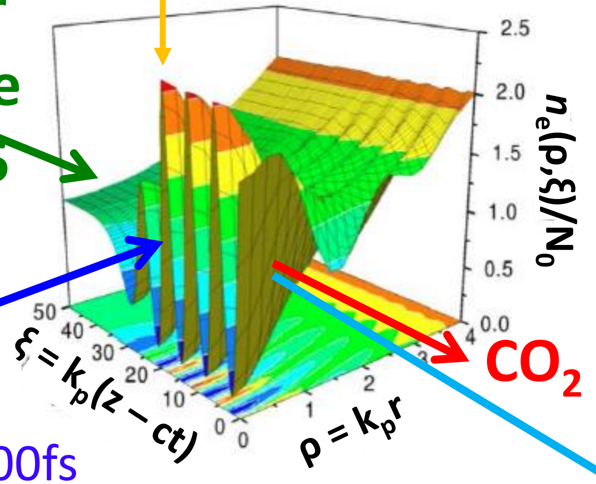
Upgraded ATF CO2 laser is needed for bubble LWFAs; meanwhile we study SM-LWFA

Self-Modulated LWFA	n_e (cm^{-3})	τ (ps)	**P** (TW)
 **ATF CO_2 Laser pulse**	~10^{18}	4	0.5
	<10^{18}	**<2**	**>2**

Laser pulse for ionization injection AE88

simulation: N. E. Andreev *et al.*, *PR-STAB* **6**, 041301 (2003)

laser Probe AE95



e^- Probe
55MeV, <200fs
AE93

CO_2 driver

Self-injected, accelerated Electrons

800nm Ti:Sapp laser ionization injection AE88

Detailed *optical visualization* of plasma wave density structure AE95

Detailed *radiographic visualization* of plasma wave E-field AE93

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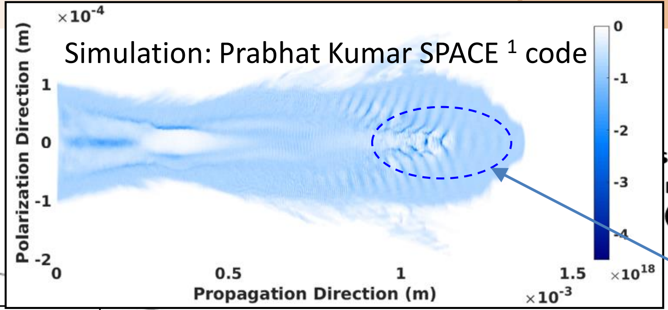
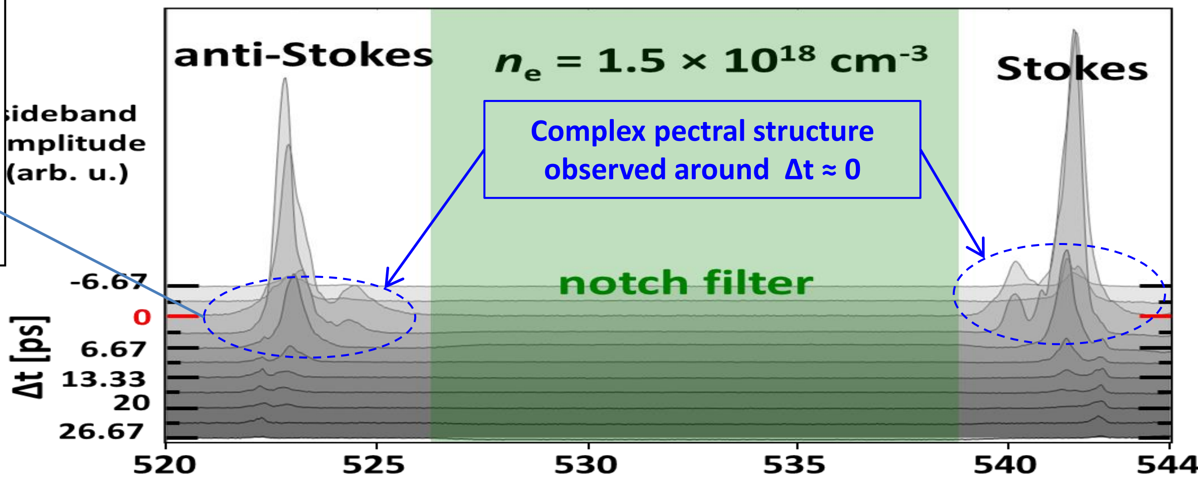
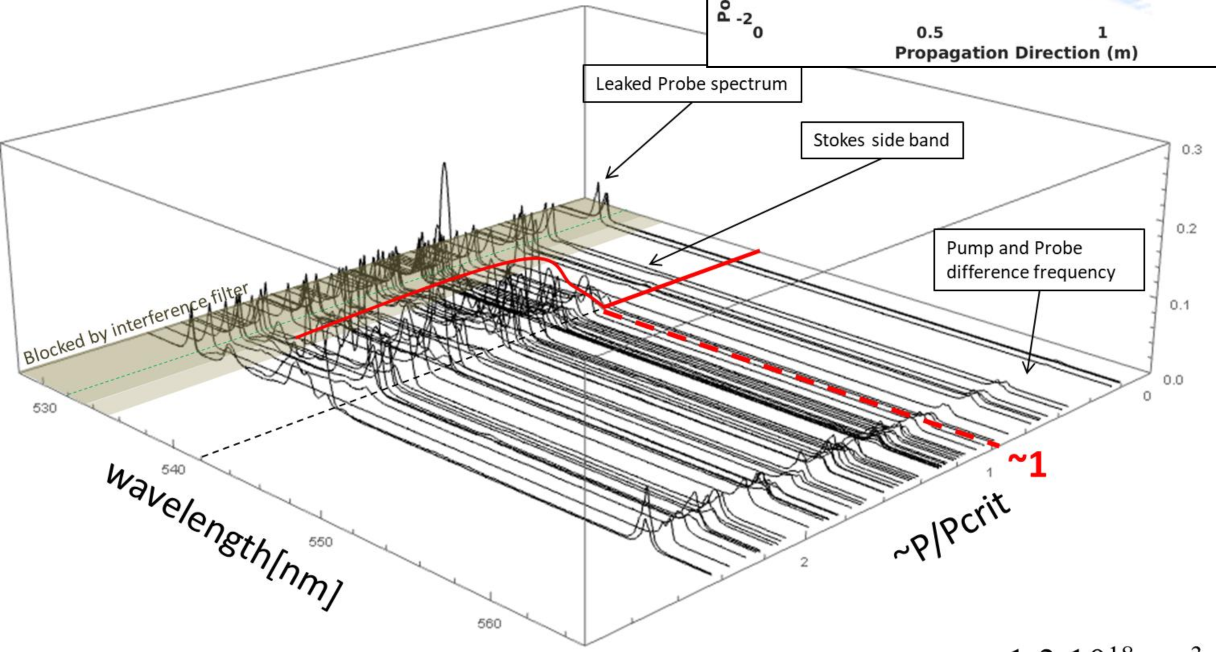
Optical detection of 0.5TW, 4ps, λ=10.6μm CO_2 laser pulse driven SM-LWFA

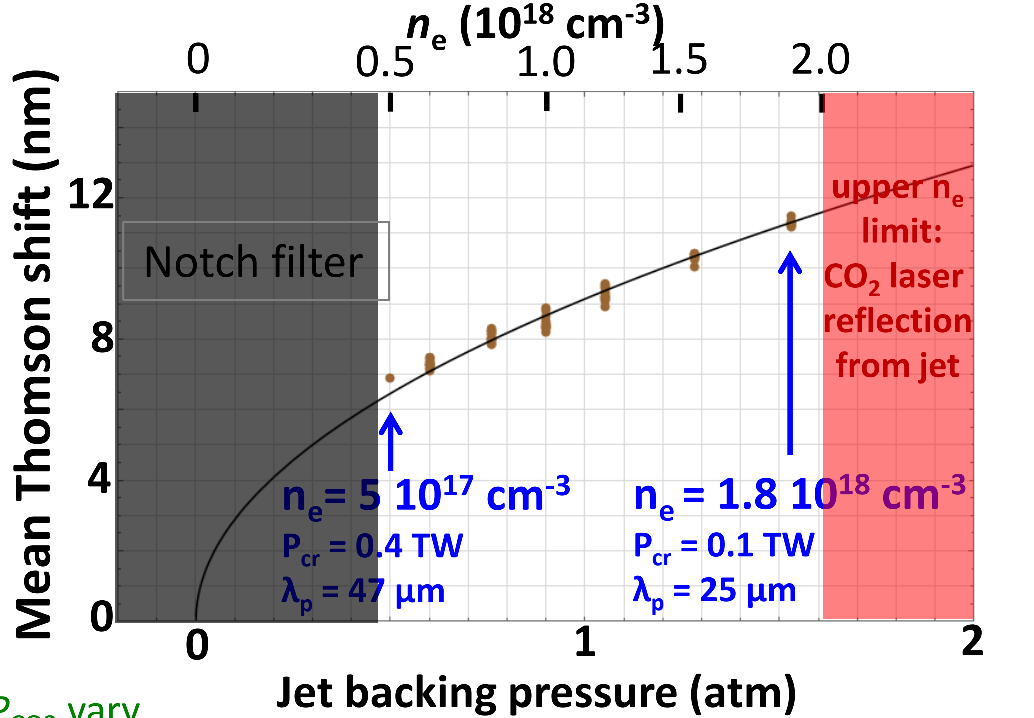
1. K. Yu, R. Samulyak, “SPACE code for beam-plasma interactions,” *Proc. IPAC*, 728 (2015)



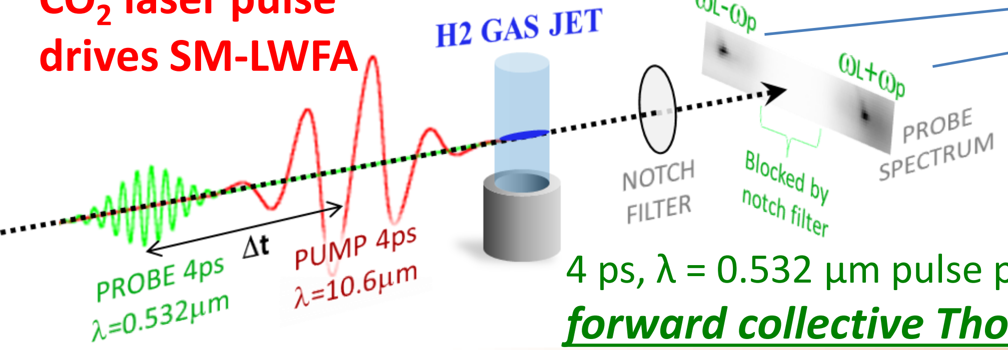




n_e ~ 1.3 10^{18} cm^{-3}



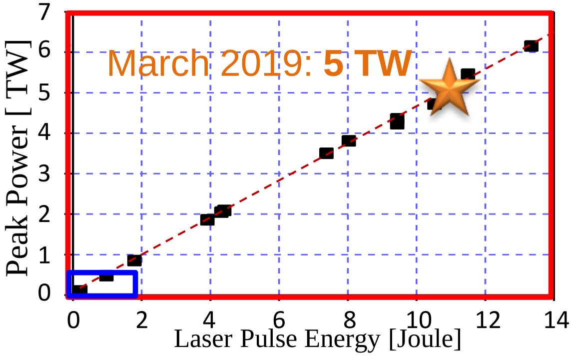
CO_2 laser pulse drives SM-LWFA



J. Welch, “Self-modulated laser wakefields driven by a CO_2 laser,” Doctoral Dissertation, UT Austin, August 2019.

4 ps, λ = 0.532 μm pulse probes wake via ***forward collective Thomson scatter*** as n_e , Δt and P_{CO2} vary.

SPACE* simulations predict self-injection threshold at P ≈ 1 TW for f /# = 2 and $n_e = 5 \times 10^{17}$ cm^{-3}



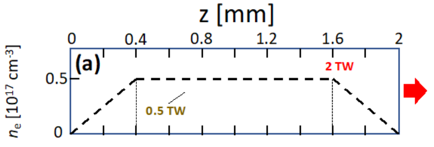
* Kumar *et al.*, *Phys. Plasmas* **28**, 013102 (2021)
Yu *et al.*, *Computer Phys. Comm.*, in press (2021)

SPACE code

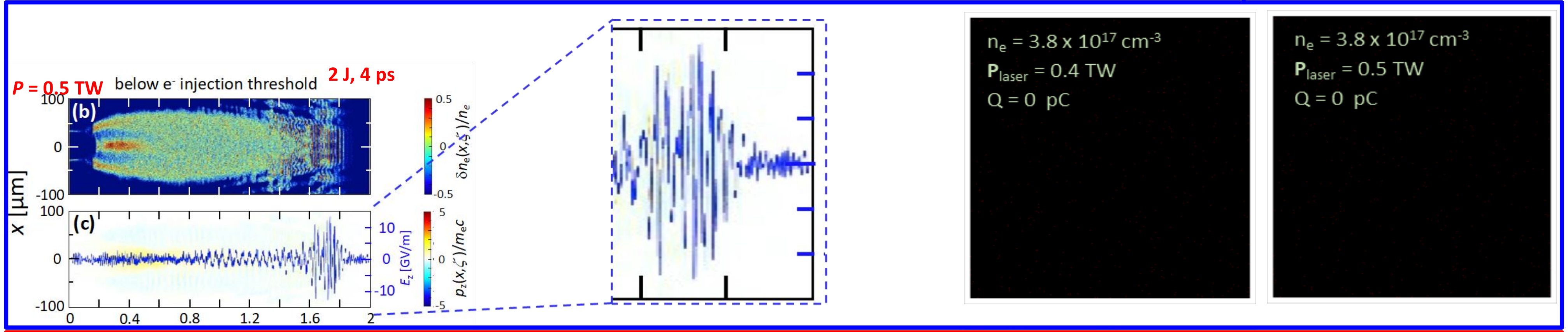
- 3D, parallel, relativistic PIC
- Yee's FDTD method solves field eq^{n}s.
- Boris-Vay pusher advances macroparticles
- algorithms for atomic physics processes induced by intense laser or particle beams:
  - ADK ionization
  - computes ionization/recombination rates on grid, then transfers them to particles

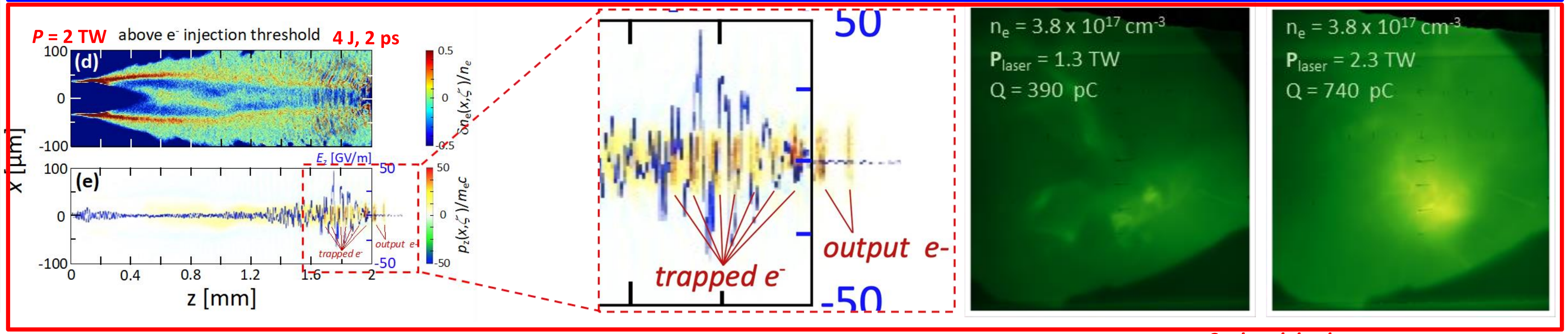
SIMULATIONS

- ions mobile
- 3D Cartesian geometry
- computational box:
  - *transverse*: 600 μm range, $dx = dy = 2$ μm (10 cells/w_0)
  - *longitudinal*: 3-5 mm range, $dz = 0.5$ μm (20 cells/λ)
- numerical convergence tested



No injection

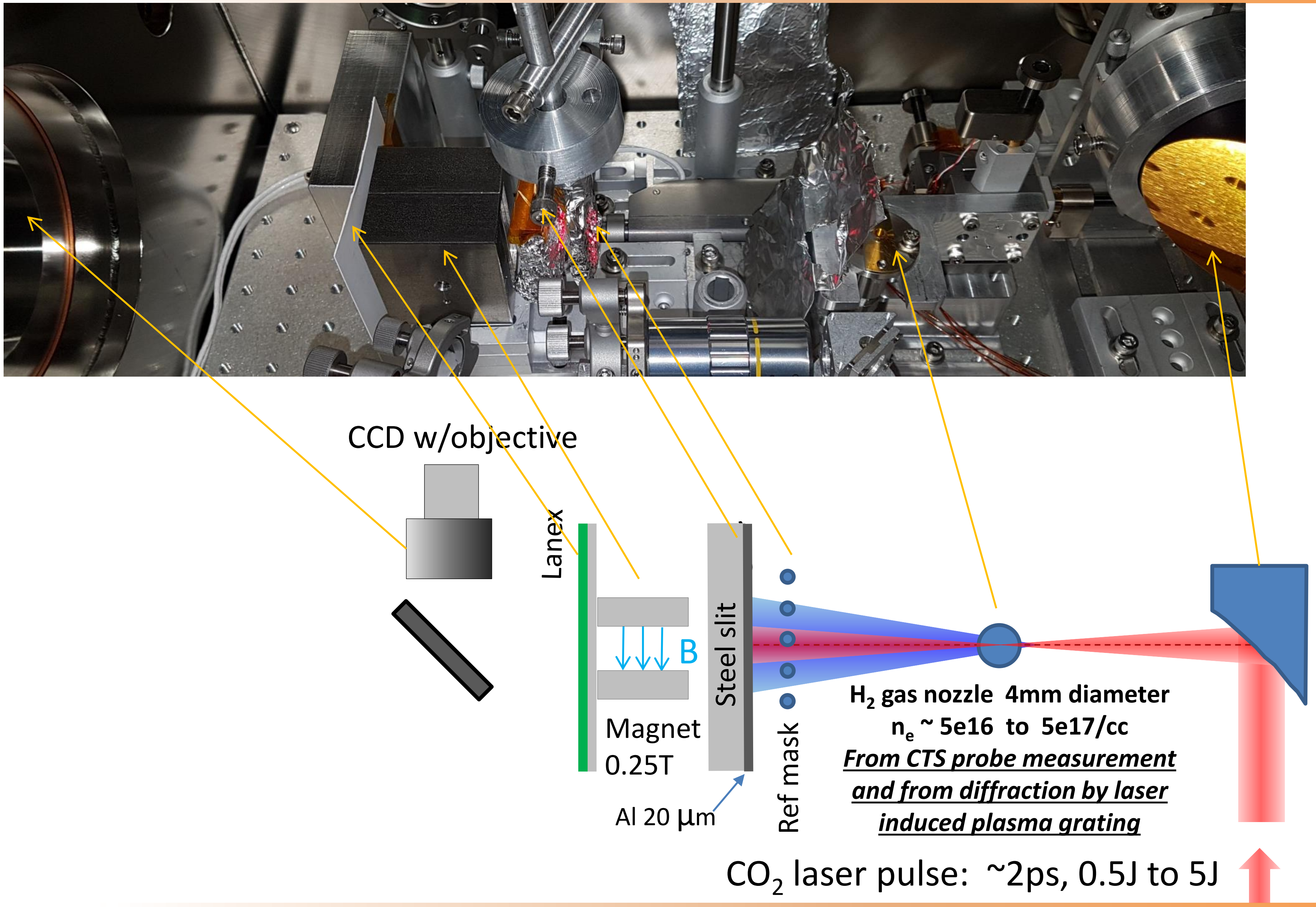




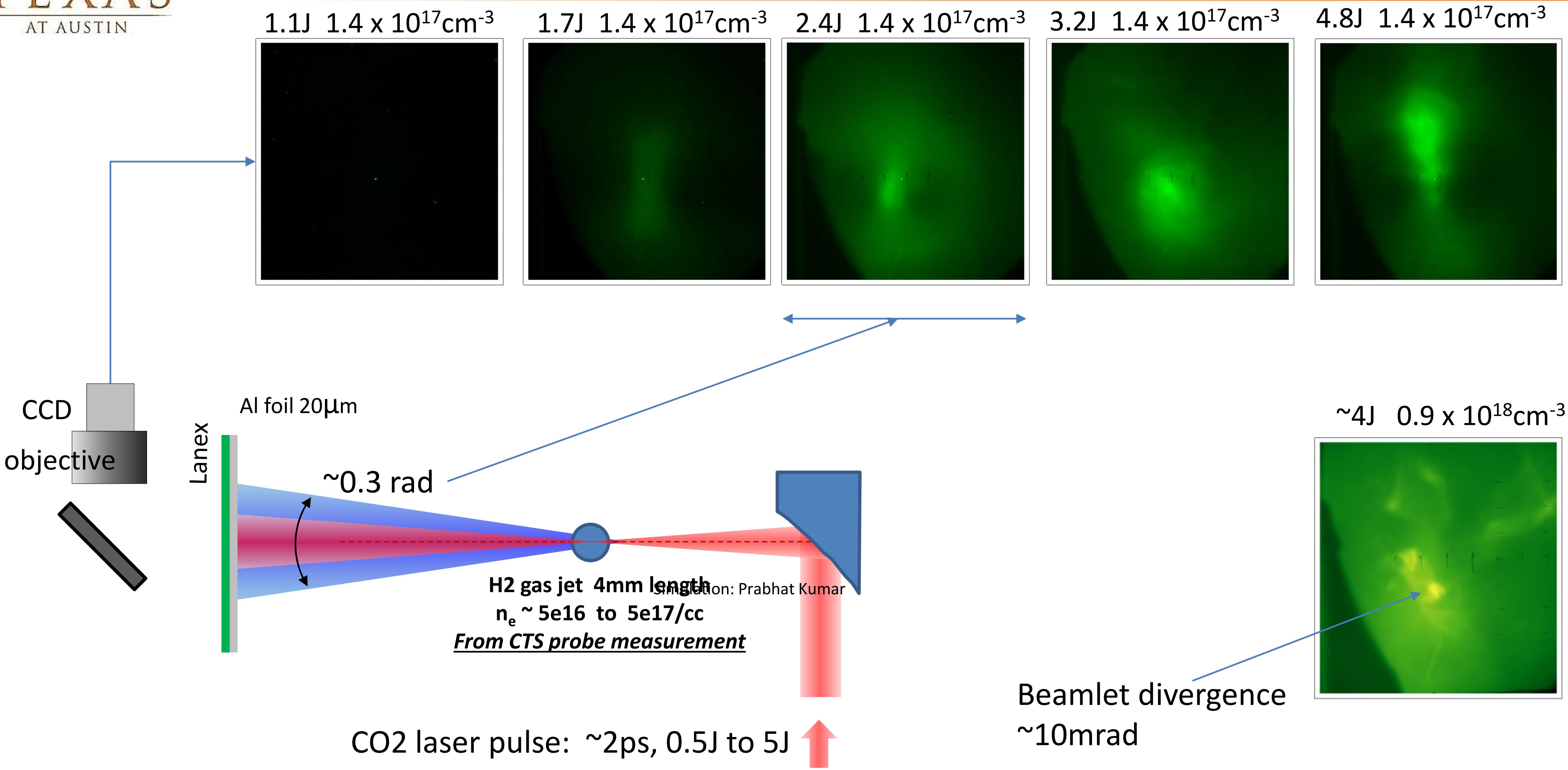
Copious injection

[1] K. Yu, R. Samulyak, "SPACE code for beam-plasma interactions," *Proc. IPAC*, 728 (2015)

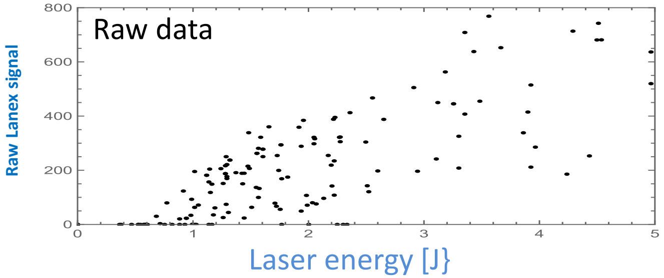
First Demonstration of SM-LWFA in the mid-IR with upgraded CO_2 laser 2ps, up to 5J

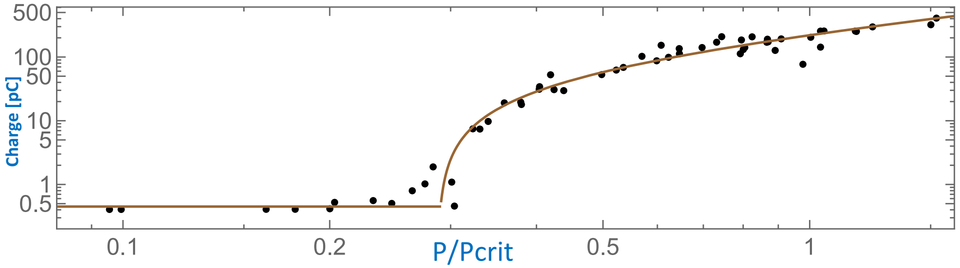


Electron beam profile

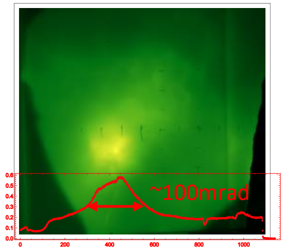


Measured charge dependence on laser energy, plasma density, and focus position



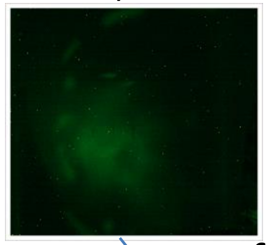


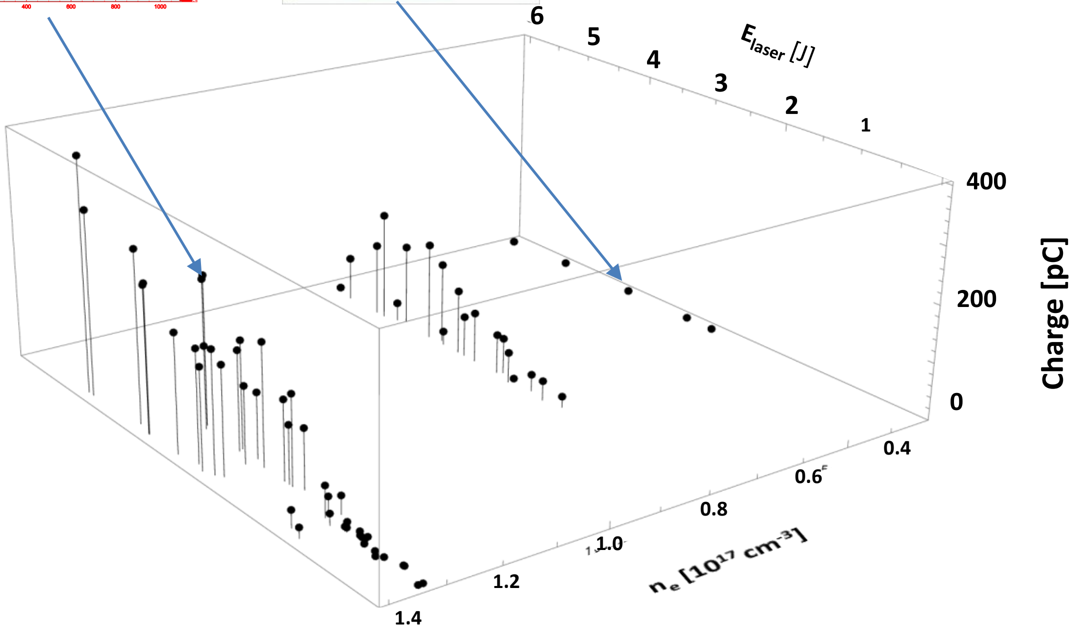
2.4J ~1.4 x 10^{17}cm^{-3}



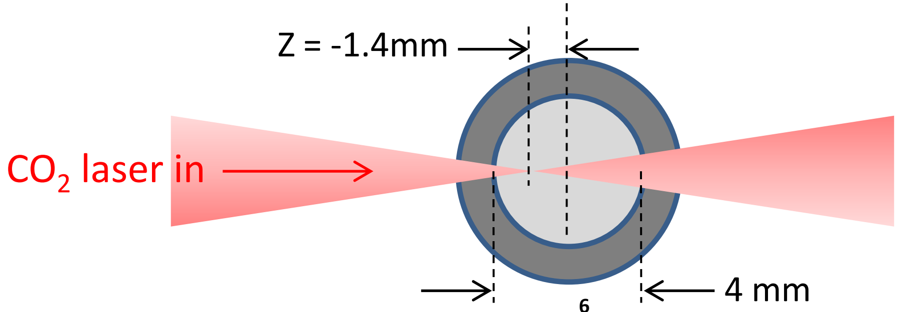
4J ~3 x 10^{16}cm^{-3}

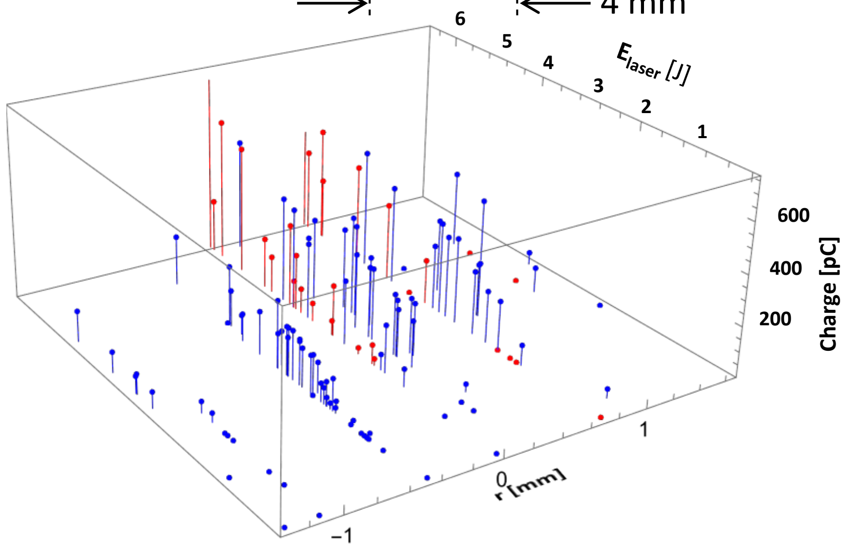
~1pC





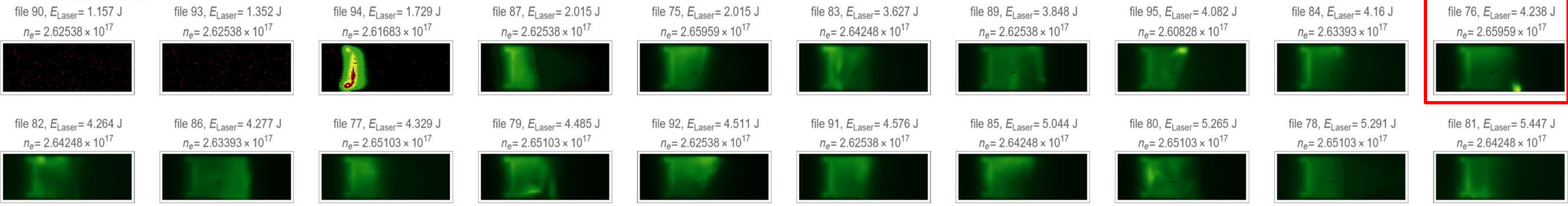
Laser vacuum focus 3mm above nozzle, at the nozzle axis

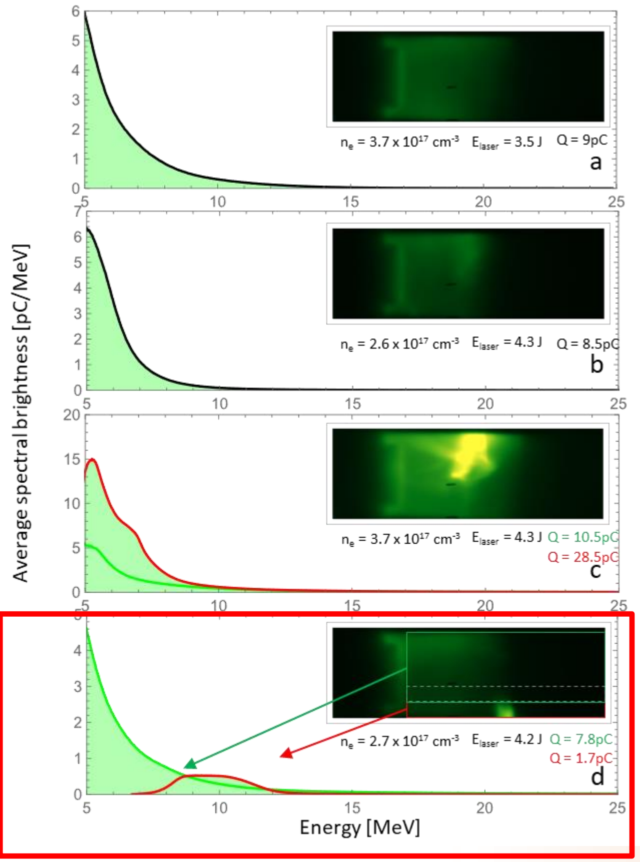


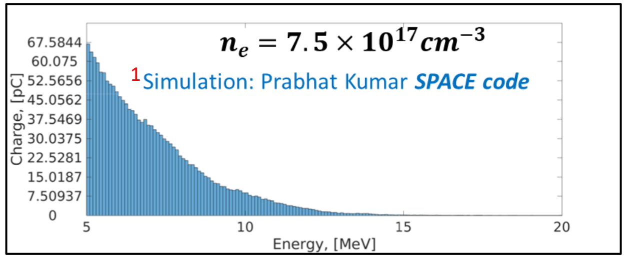


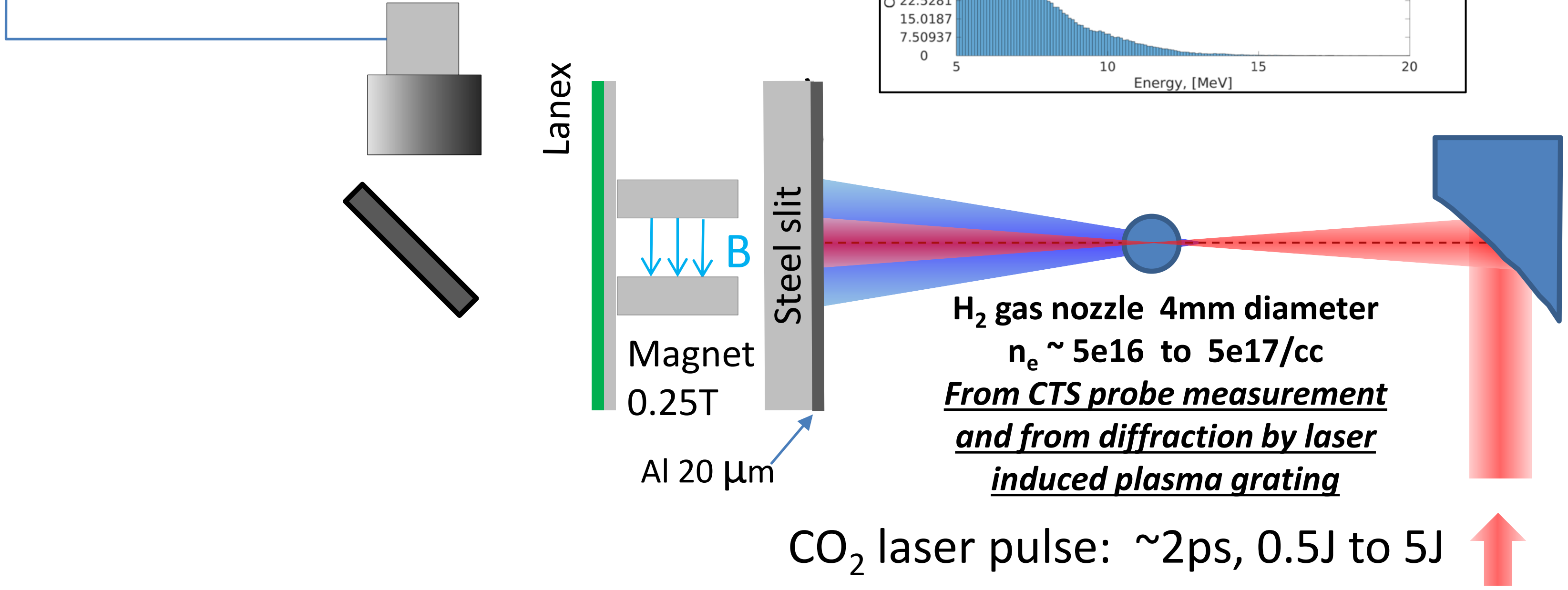
Constant density

Example sequence of electron energy spectra at constant plasma density and increasing E_{laser}





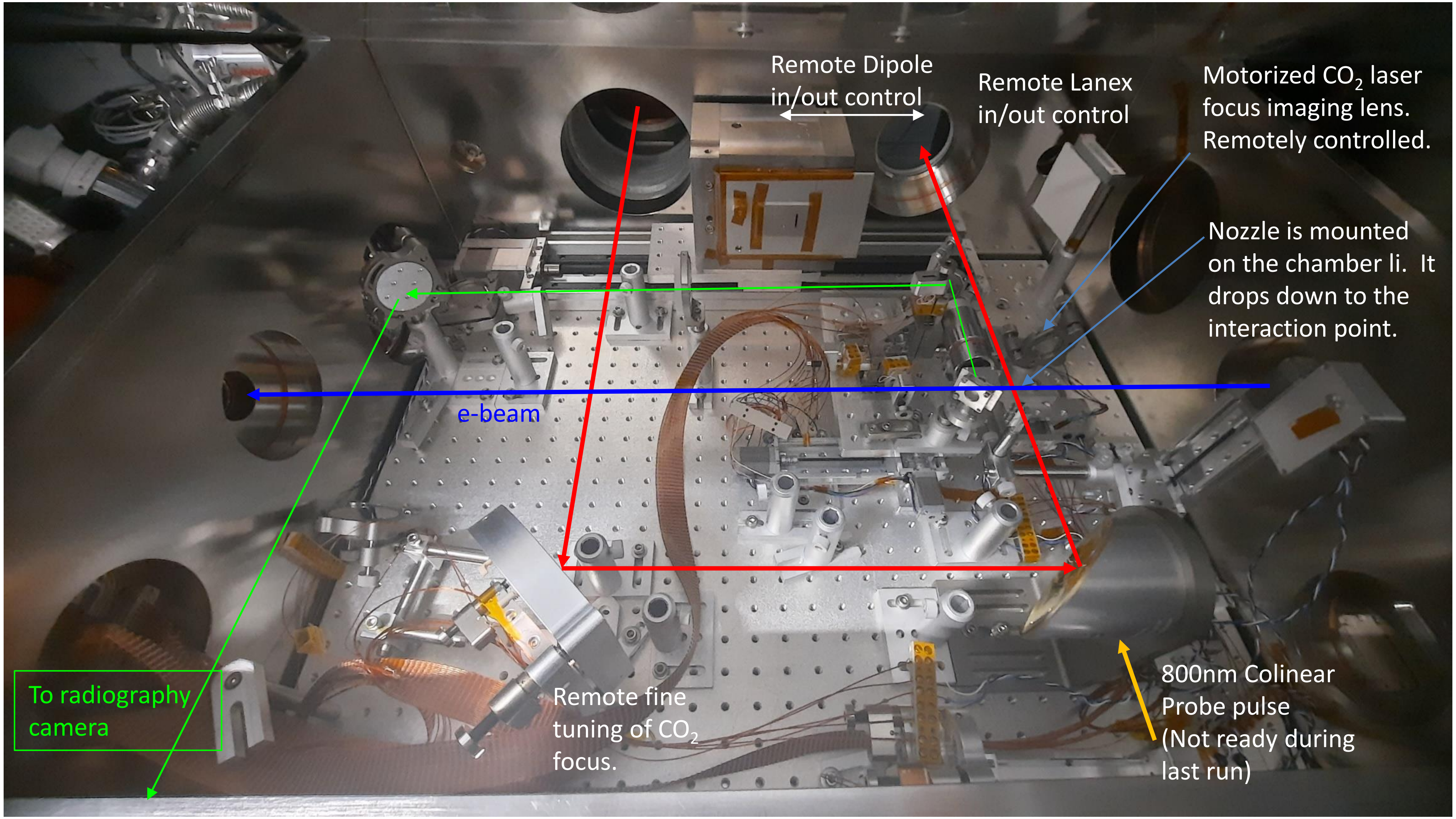




[1] K. Yu and R. Samulyak, "SPACE code for beam-plasma interaction," in 6th IPAC (2015), pp. 728-730.

Newest configuration of the experiment.

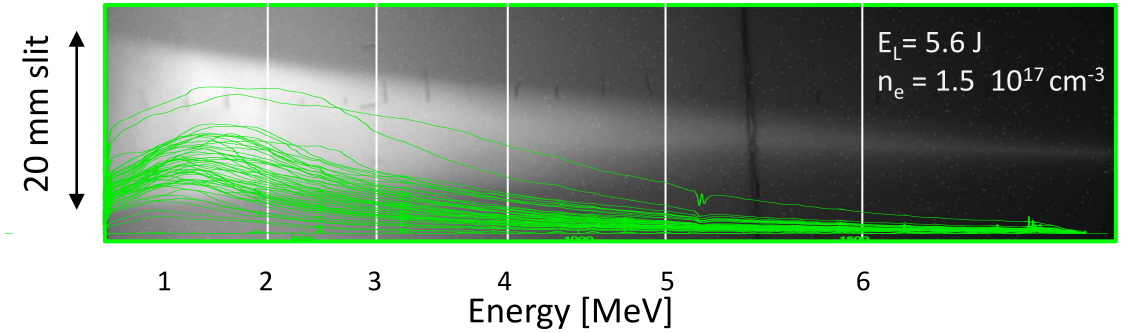
Electron spectrometer and beam profile cameras behind the chamber

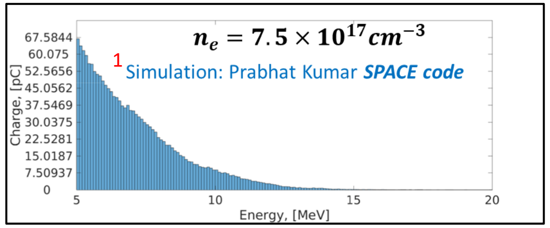


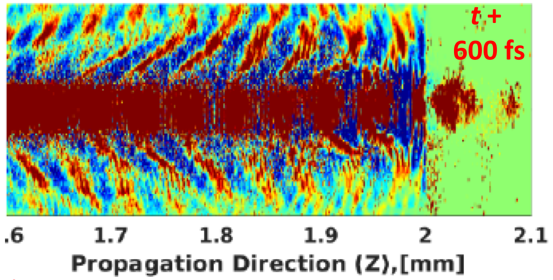
Raw result samples from second run

Two spectrometer configurations: Low and High energy

low energy configuration

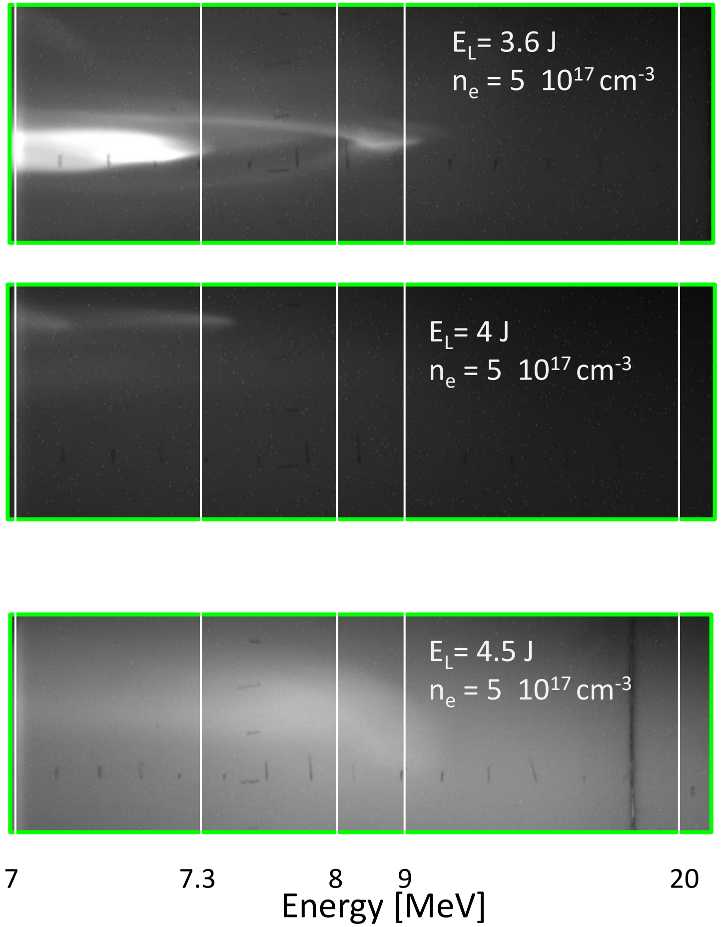


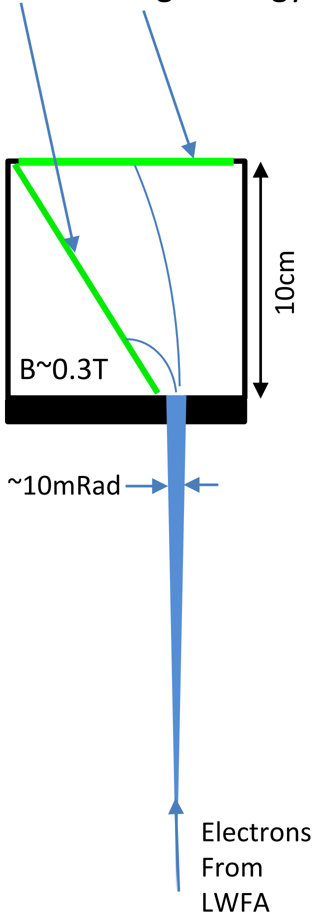




[1] Laser: λ = 9.2 µm, w_0 = 20 µm, τ = 2 ps, E = 4 J
Plasma: n_{e0} = 5 x 10^{17} cm^{-3}

High energy configuration





Under some combinations of laser energy, hydrogen density, and nozzle position relative to the laser focus, the core of the electron beams becomes less divergent and more intense:

[1] K. Yu and R. Samulyak, "SPACE code for beam-plasma interaction," in 6th IPAC (2015), pp. 728-730.

Summary and Future Plans

1) Copious electron self-injection and acceleration has been demonstrated from a SM-LWFA driven by ATF's 2ps, 5TW, single pulse CO_2 laser.
2) Electron beamlets with divergence as low as ~10mRad have been observed.
3) Electron energies up to 10 MeV and sometimes higher have been observed.
4) Although most spectra are continuous with an exponentially decaying tail at high energies, a number of cases were recorded with a narrow bandwidth peak at the high end of the spectrum, leading to the conclusion that a strongly nonlinear regime is being reached.
5) Very low injection thresholds have been observed. The smallest accelerated charge was observed at about 10^{16}cm^{-3}, driven by a 5TW pulse.

1) Resume optical probe studies (AE95) after switching to the new Ti:Sapp generated 800nm probe beams, and subsequently to larger wavelengths (Thomson scattering, transverse shadowgraphy, frequency domain interferometry/holography). Short pulse 800nm probe will increase temporal resolution. Moving toward longer wavelengths allows stretching optical probing sensitivity toward lower plasma densities.
2) Continued study of electron spectra, profiles, charge, together with optical plasma probe and radiographic field measurement (AE93)
3) Faraday rotation measurement of magnetic fields associated with SM-LWFA. Additionally, this diagnostic is more sensitive at lower densities than interferometry and is sensitive to injected charge.
4) Ultimate goal is to transition to blowout regime characterization with, and without, external injection from the linac, or from optical ionization (AE88),when the CO_2 laser upgrades allow this.

Thank you!

Products

1. J. Welch, "Self-modulated laser wakefields driven by a CO_2 laser," Doctoral Dissertation, UT Austin, August 2019.
2. P. Kumar, et al., "Simulation study of CO2 laser-plasma interactions and self-modulated wakefield acceleration", Phys. Plasmas 26, 083106 (2019)
3. Kumar, P., et al., "Evolution of the self-injection process in long-wavelength infrared laser-driven wakefield accelerators," Phys. Plasmas 28, 013102 (2020).
4. R. Zgadzaj, "CO_2-laser-driven wakefield acceleration," presented at the 20^{th} Advanced Accelerator Concepts Workshop, Hauppauge, NY, Nov. 6-11, 2022.
5. R.Zgadzaj, I. Petrushina, et al., "Terawatt CO2-laser-driven plasma acceleration of electrons," in preparation for Nat. Comm. 2023
6. R. Zgadzaj, "CO_2-laser-driven wakefield acceleration," invited presentation, Laser-Plasma Accelerator Workshop, Lagos, Portugal, March 6-10, 2023.
7. Y. Cao, "Emittance preservation of a CO_2-laser driven wakefield acceleration with external injection," presented at the 20^{th} Advanced Accelerator Concepts Workshop, Hauppauge, NY, Nov. 6-11, 2022.
8. Y. Cao, et. al., "Emittance preservation of a CO2-laser driven wakefield acceleration with external injection," to be submitted for publication in Proceedings of the 20th Advanced Accelerator Concepts Workshop, 2022.

Electron Beam Requirements

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*	
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	
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*	
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.*	
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	

CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 CPA Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2*
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.*	*0-5*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2 or less*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available in FY20*	*5 and greater if available*
	M^2	---	~2		*~2*
	Repetition Rate	Hz	0.05		*0.05*
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	*Adjustable Linear and Circular*

Other Experimental Laser Requirements

Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments	Requested Values
Central Wavelength	nm	800	800	*Stage I parameters should be achieved by mid-2020, while Stage II parameters are planned for late-2020.*	*800nm*
FWHM Bandwidth	nm	20	13		*13nm*
Compressed FWHM Pulse Width	fs	<50	<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.*	*75fs*
Chirped FWHM Pulse Width	ps	≥50	≥50		*50ps*
Chirped Energy	mJ	10	200		***10mJ***
Compressed Energy	mJ	7	100		***5mJ***
Energy to Experiments	mJ	>4.9	>80		***5mJ***
Power to Experiments	GW	>98	>1067		

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	
Energy	mJ	5		
Pulse Width	ps	14		
Wavelength	nm	532	*Frequency doubled*	*532nm*
Energy	mJ	0.5		*0.5mJ*
Pulse Width	ps	10		*2-3ps*

Special Equipment Requirements and Hazards

- Electron Beam
  - Please indicate any special equipment that you expect to need, including (but not limited to) the transverse deflecting cavity, shaped bunch using mask technique, plasma capillary discharge system, bolometer/interferometer setup etc.:
- CO_2 Laser
  - Please note any specialty laser configurations required here: polarization control
- Ti:Sapphire and Nd:YAG Lasers
  - Please note any specialty non-CO_2 laser configurations required here: Doubled Yag and Ti:Sapphire laser beams at LWFA chamber: Compressed Ti:Sapphire laser at LWFA chamber
- Hazards & Special Installation Requirements
  - Large installation (chamber, insertion device, etc.):N
  - Cryogens:N
  - Introducing new magnetic elements: Spectrometer magnet <1T
  - Introducing new materials into the beam path: N
  - Any other foreseeable beam line modifications: Compressor for electron beam

Experimental Time Request

CY2023 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		0
Laser* Only (in FEL Room)		0
Laser* + Electron Beam	80	120

Time Estimate for Remaining Years of Experiment (including CY2023-25)

Capability	Setup Hours	Running Hours
Electron Beam Only	0	0
Laser* Only (in FEL Room)	0	0
Laser* + Electron Beam	240	720

* Laser = Near-IR or LWIR (CO_2) Laser