ATF User's Meeting
26-28 March 2024

Toward bubble-regime CO_2-laser-driven wakefield acceleration*

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Collaborators:

University of Texas at Austin:
Faculty: M. C. Downer
Research Scientist: R. Zgadzaj
PhD students: Y. Cao, B. Dinh, T. Araujo

UCLA:
Faculty: C. Joshi

Stony Brook University:
Faculty: Navid Vafaei-Najafabadi, Roman Samulyak, V. N. Litvinenko
Postdoc: N. Pathak
PhD Students: A. Cheng, A. Gaikwad, B. Romasky, E. Trommer

Brookhaven NL:
ATF Director: M. A. Palmer
Research Scientists: M. Babzien, M. Fedurin, R. Kupfer, K. Kusche, W. Li, I. V. Pogorelsky, M. N. Polyanskiy

* optical diagnosis emphasis (complementary to Navid's electron radiography emphasis)

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Goal: develop LWFAs that routinely produce e-beams with $\Delta E_e/E_e$ and $\mathcal{E}_n$ low enough to drive XFELs

Key ingredients: *1) Large plasma bubbles ($R_b \gtrsim 0.3$ mm) $\Rightarrow n_e \lesssim 10^{16}$ cm^{-3}

**2) External injection of low $\Delta E_e/E_e$, low $\mathcal{E}_n$ e-bunches

* Efficiently excited by LWIR laser pulses uniquely realizeable at ATF

- Pogorelsky *et al.*, *Phys. Rev. Accel. Beams* **19**, 091001 (2016); Kumar *et al.*, *Phys. Plasmas* **28**, 013102 (2021)

** Synchronized, compressed ATF linac bunches uniquely enable 1st-generation experiments.

The Proposed Project builds upon AE71 and AE95 success.

Project #	CO_2 laser parameters	Main results
AE-71	2 J, 4 ps, 0.5 TW, 10.3 μm	• Generation, characterization of self-modulated (SM) wakes. No electrons. [2]
AE-95	4 J, 2 ps, 2 TW, 9.2 μm	• Self-injected MeV electrons produced at $n_e \gtrsim 3 \times 10^{16}$ cm^{-3} [1] • Quasi-monoenergetic, collimated features observed. [2]
Proposed Project	5-20 J, < 2 ps, 5-20 TW	• Excite, characterize $R_b \sim 0.3$ mm bubbles at $n_e \sim 10^{16}$ cm^{-3} w/o self-injection • Inject e^- from ATF linac, characterize $\Delta E_e/E_e$ and $\mathcal{E}_n$

[1] Predicted by Kumar *et al.*, *Phys. Plasmas* **26**, 083106 (2019)

[2] Zgadzaj *et al.*, *Nat. Comms.*, in press (2024)

Year 1-2 Scientific Goals

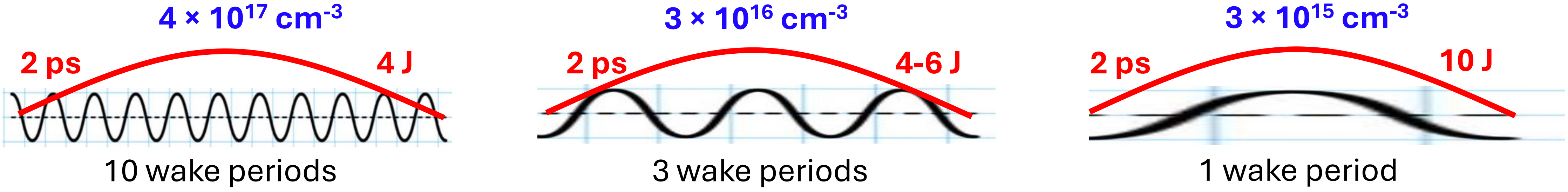
UTexas team: Dr. R. Zgadzaj, PhD student B. Dinh

Constraints:
- CO_2 laser at or near current parameters: (4 – 10 J, 2 ps, 2 - 5 TW)
- No linac e-beam needed (Navid's group is developing e-beam probes)
- Ti:S probe laser at current parameters
- Use existing AE95 infrastructure (gas jet, magnetic spectrometer, etc.)

1) Discover low-n_e, high-P_L limits of self-injected LWIR-driven WFA.

- Can we reach the full bubble regime while still self-injecting?

- In AE95 (4 J, 2 ps) we observed collimated quasi-monoenergetic electrons only at $n_e = 4 \times 10^{17}$ cm^{-3}.
  We generated electrons down to $n_e = 3 \times 10^{16}$ cm^{-3}, but did not have time to spectrally analyze them.
  Will quasi-monoenergetic component strengthen for $n_e < 4 \times 10^{17}$ cm^{-3} and $P_L > 2$ TW?



- **Widen experimental conditions**: H_2 → He target; lin → circ pol drive pulse; downramp & ionization injection
- Understand self-injection limits thru **simulations** (with Samulyak).

Year 1-2 Scientific Goals (cont'd)

2) Upgrade optical diagnostics of wakes in low-n_e plasma

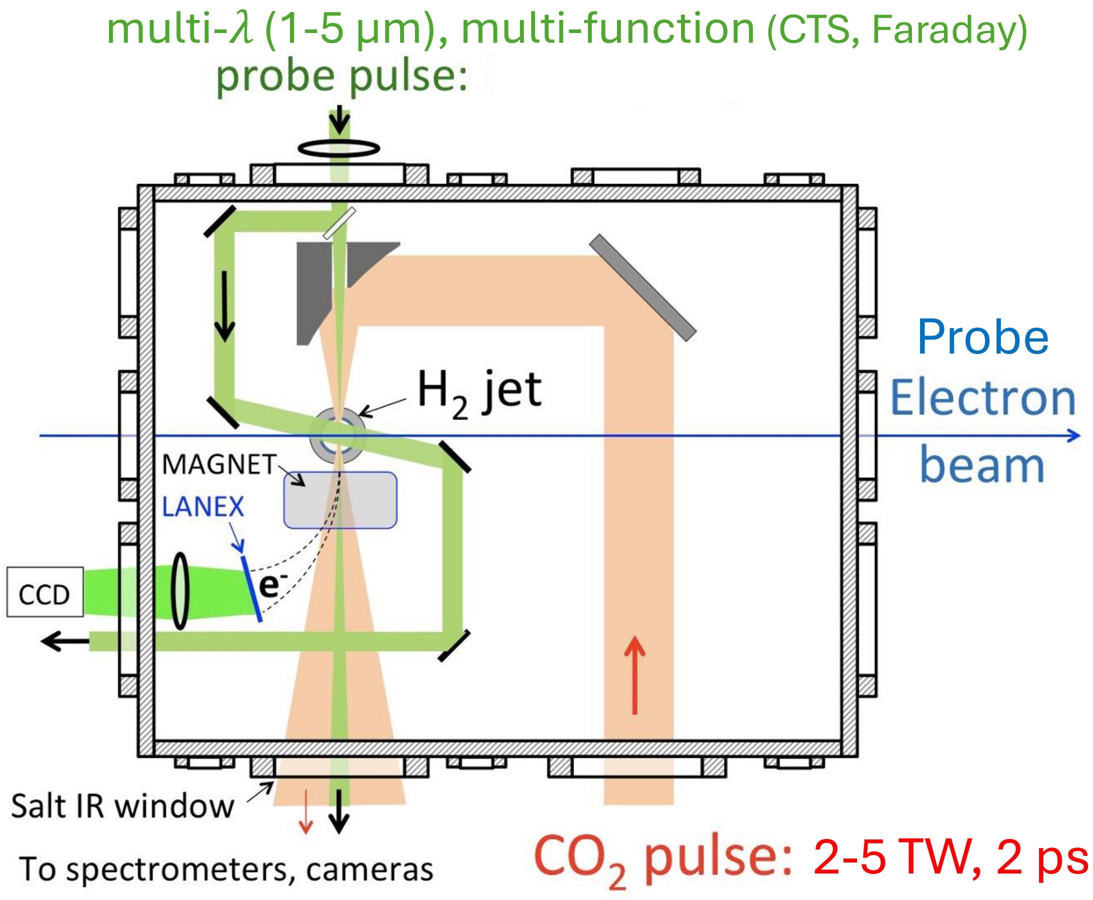
(complement e-beam probes that Navid's group is leading)

1) Apply collective Thomson scatter (CTS) ***probe during e^- acceleration*** (AE95: only empty wakes probed) ⇒ observe ***beam-loading effects on wake structure & dynamics***.

2) ***Upgrade CTS sensitivity to $10^{15} < n_e < 10^{17}$ cm^{-3} plasmas***, using spatial-spectral filtering techniques developed at UCLA.
   Filip et al., "CTS diagnostic system for detection of relativistic waves in low-density plasmas," *Rev. Sci. Instrum*. **74**, 3576 (2003)
   (AE95: CTS used only for $n_e \geq 4 \times 10^{17}$ cm^{-3})

3) Add a ***transverse CTS probe*** to complement current co-propagating probe ⇒ ***diagnose wake evolution*** due to self-focusing, mismatched propagation, wake formation, electron injection, and beam loading.

4) Augment current λ = 1 μm probe with ***λ = 3, 5 μm probes*** derived from 3rd, 2nd harmonics of split-off CO_2 pulses generated in $AgGaSe_2$ crystals ⇒ **improve sensitivity to low-n_e plasma structures, eliminate pu-pr timing jitter.** Detect with cooled InGaAs or InSb CCD camera.



Proposed upgraded optical diagnostic system
- upgraded CTS + Faraday probes
- longitudinal + transverse probes
- 1 μm + 3, 5 μm CO_2 harmonic probes

Year 1-2 Scientific Goals (cont'd)

2) Upgrade optical diagnostics of wakes in low-n_e plasma (cont'd)

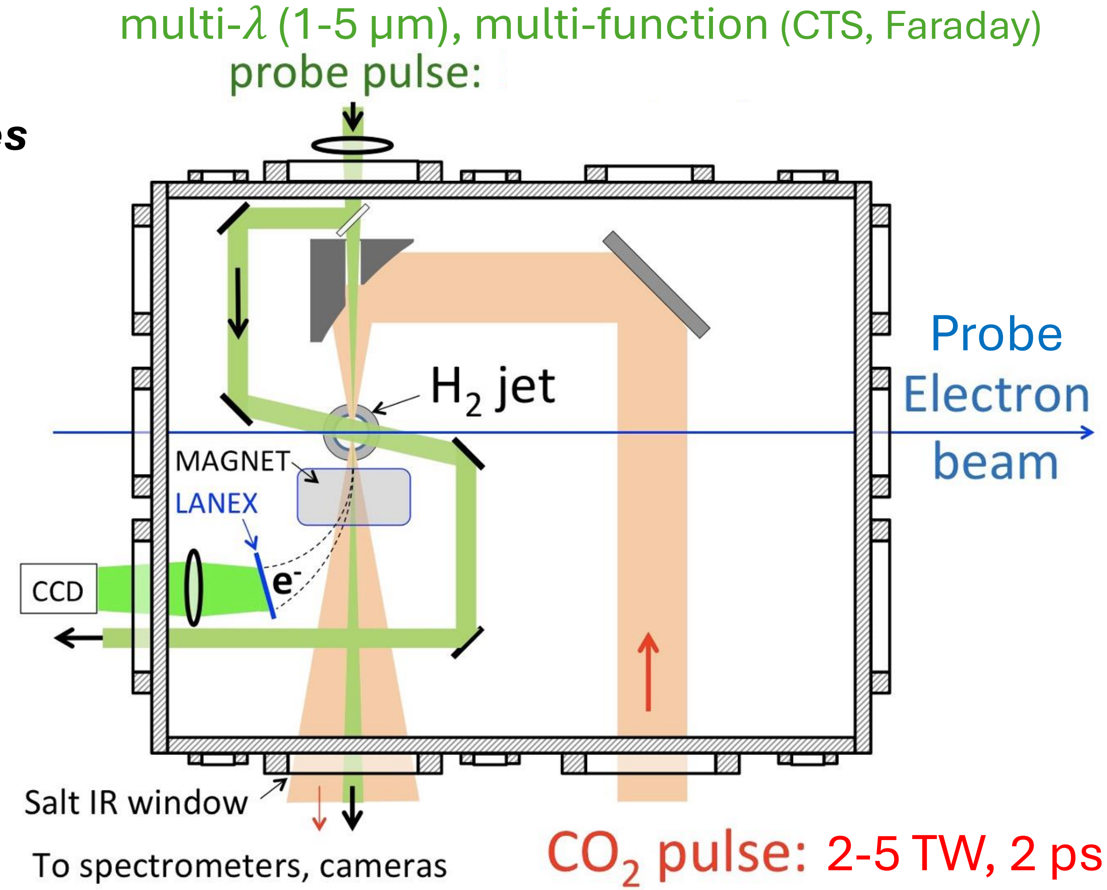
5) Observe probe ***Faraday rotation*** due to kilo-T fields from high peak currents ⇒ visualize ***magnetized plasma structures at $n_e < 10^{17}$ cm^{-3}***.

Chang *et al.*, "Faraday rotation study of plasma bubbles in GeV wakefield accelerators," *Phys. Plasmas* **28**, 123105 (2021)

These upgraded diagnostics will improve our ability to observe large plasma bubbles in $n_e \sim 10^{16}$ cm^{-3} plasma.

Development of effective diagnostics of low-n_e wakes is a forefront challenge for WFA science:

Downer *et al.*, "Diagnostics for plasma-based electron accelerators," *Rev. Mod. Phys.* **90**, 035002 (2018)



Proposed upgraded optical diagnostic system

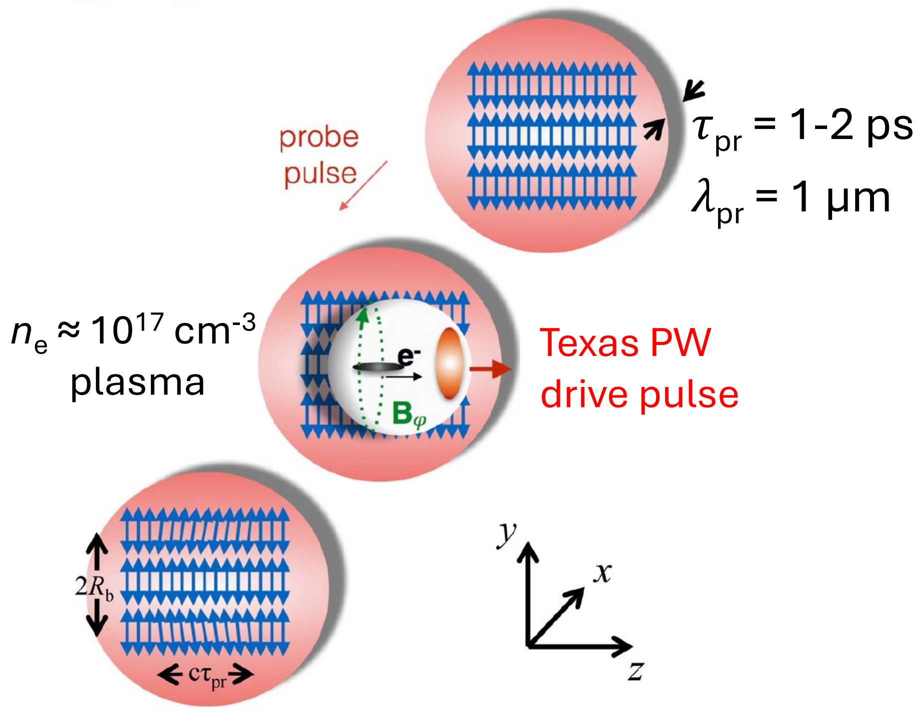
- upgraded CTS + Faraday probes
- longitudinal + transverse probes
- 1 μm + 3, 5 μm CO_2 harmonic probes

Faraday rotation can image plasma bubbles in low-n_e plasma

Texas Petawatt

$n_e \approx 10^{17}$ cm^{-3}: [1] Chang *et al.*, "Faraday rotation study of plasma bubbles in GeV wakefield accelerators," *Phys. Plasmas* **28**, 123105 (2021)

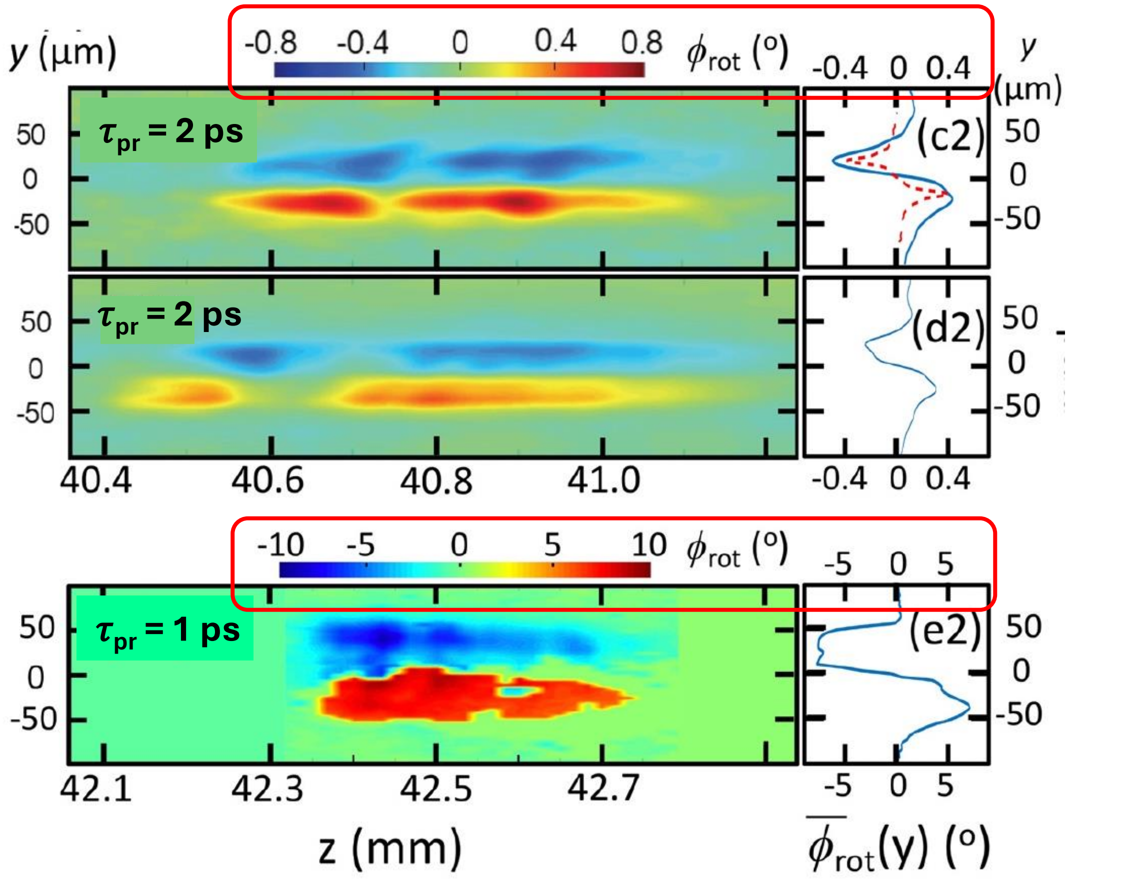
$n_e > 10^{19}$ cm^{-3}: [2] Kaluza *et al.*, *Phys. Rev. Lett.* **105**, 115002 (2010); [3] Buck *et al.*, *Nat. Phys.* **7**, 453 (2011).



$$\phi_{rot} = \frac{e}{2m_e c n_{cr}^{(pr)}} \int_\ell n_e \mathbf{B}_\varphi \cdot ds$$

large $\mathbf{B}_\varphi$ and l compensate small $n_e/n_{cr}^{(pr)}$

Faraday "streaks" of magnetized plasma bubble walls in $n_e \approx 10^{17}$ cm^{-3} plasma

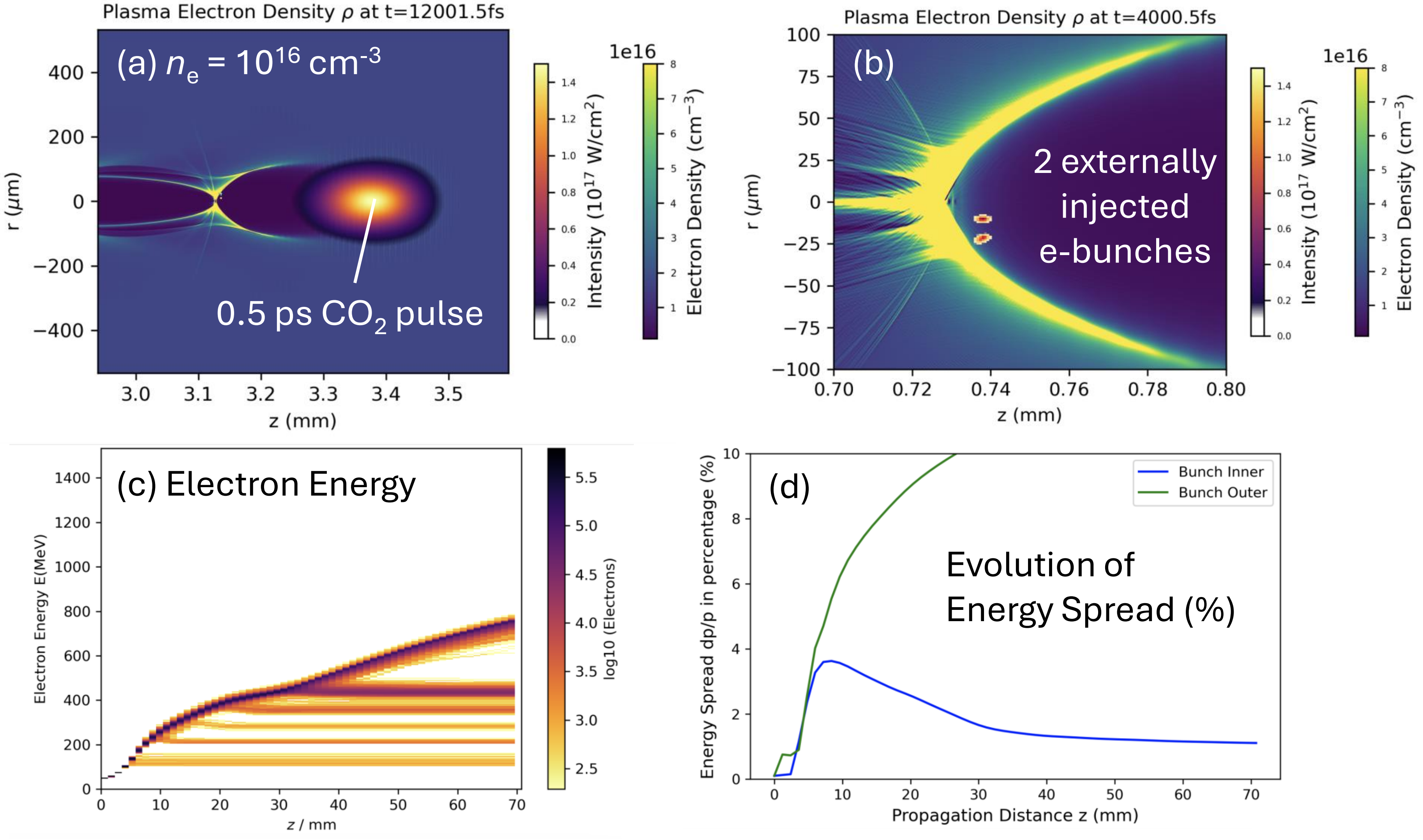


$\phi_{rot}^{(1)}$ at $n_e \approx 10^{17}$ cm^{-3} ≥ $\phi_{rot}^{(2,3)}$ observed at $n_e \approx 10^{19}$ cm^{-3}

Year 1-2 Scientific Goals (cont'd)

3) Understand $\Delta E_e/E_e$, emittance growth in large bubbles thru simulations.

(PhD student Yuxuan Cao)

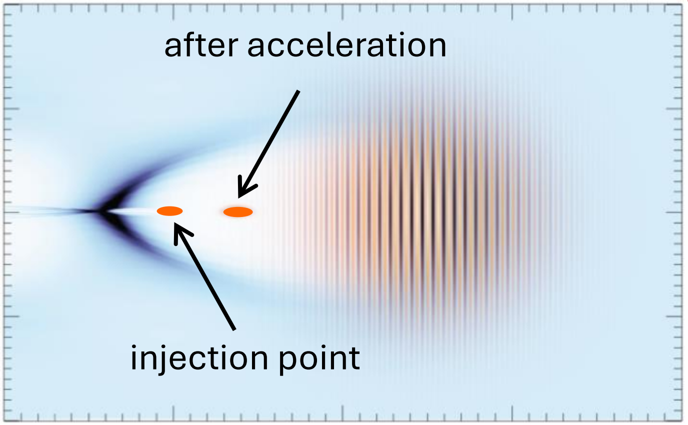


FB-PIC simulations by Y. Cao

- PIC simulations take a long time --- too many parameters to vary to search for optimum.
- YC will focus on quasi-static bubbles.
- YC will develop machine-learning approaches to optimize the external injection process, and determine what ΔE/E and emittance are achievable in principle.

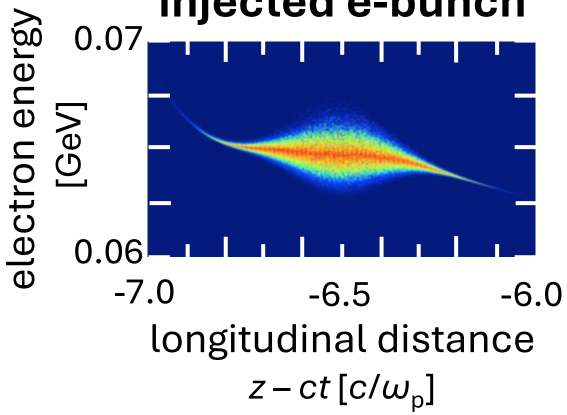
OSIRIS* quasi-3D simulations show that large bubbles preserve energy spread & spin polarization of strategically injected e-bunches during acceleration

Simulations by Z. Nie, F. Li and W. B. Mori (UCLA)

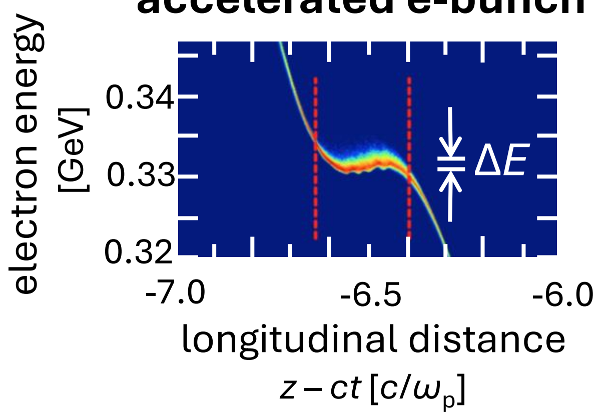


$\Delta E/E \approx 0.25\%$

E **= 65 MeV,**
Δ*E* **= 0.5 MeV**
injected e-bunch

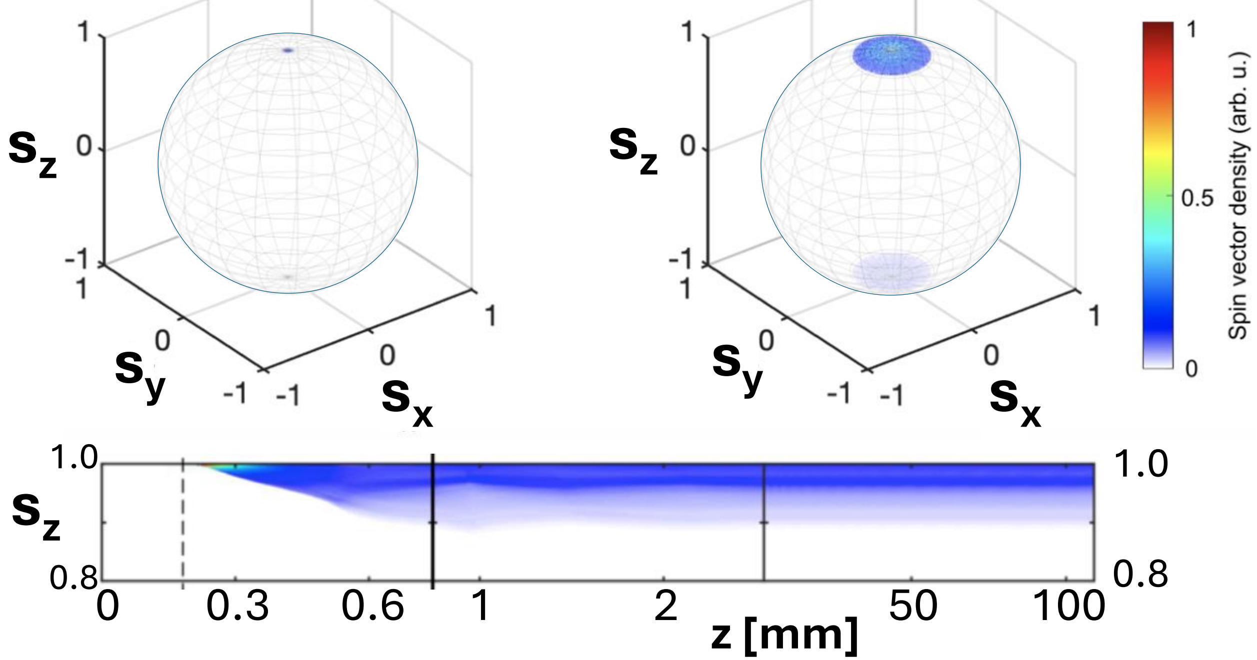


E **= 330 MeV,**
Δ*E* **= 0.8 MeV**
accelerated e-bunch



spin-polarized injected e-bunch

slightly depolarized accelerated e-bunch



- Depolarization due to spin precession is ~ few %
- Depends on coordinates of injection point
- Occurs predominantly from $\gamma = 1 \rightarrow 10$, constant thereafter

Simulation parameters:

λ_{laser}	a_0	τ_{laser}	n_p	Q_{tr}	γ_b	ϵ_n
10.6 um	4	530 fs	8.5e+15 cm^{-3}	2 nC	50 MeV	1 um

* Fonseca *et al.*, *PPCF* **55**, 124011 (2013)

Year 3 Scientific Goal:

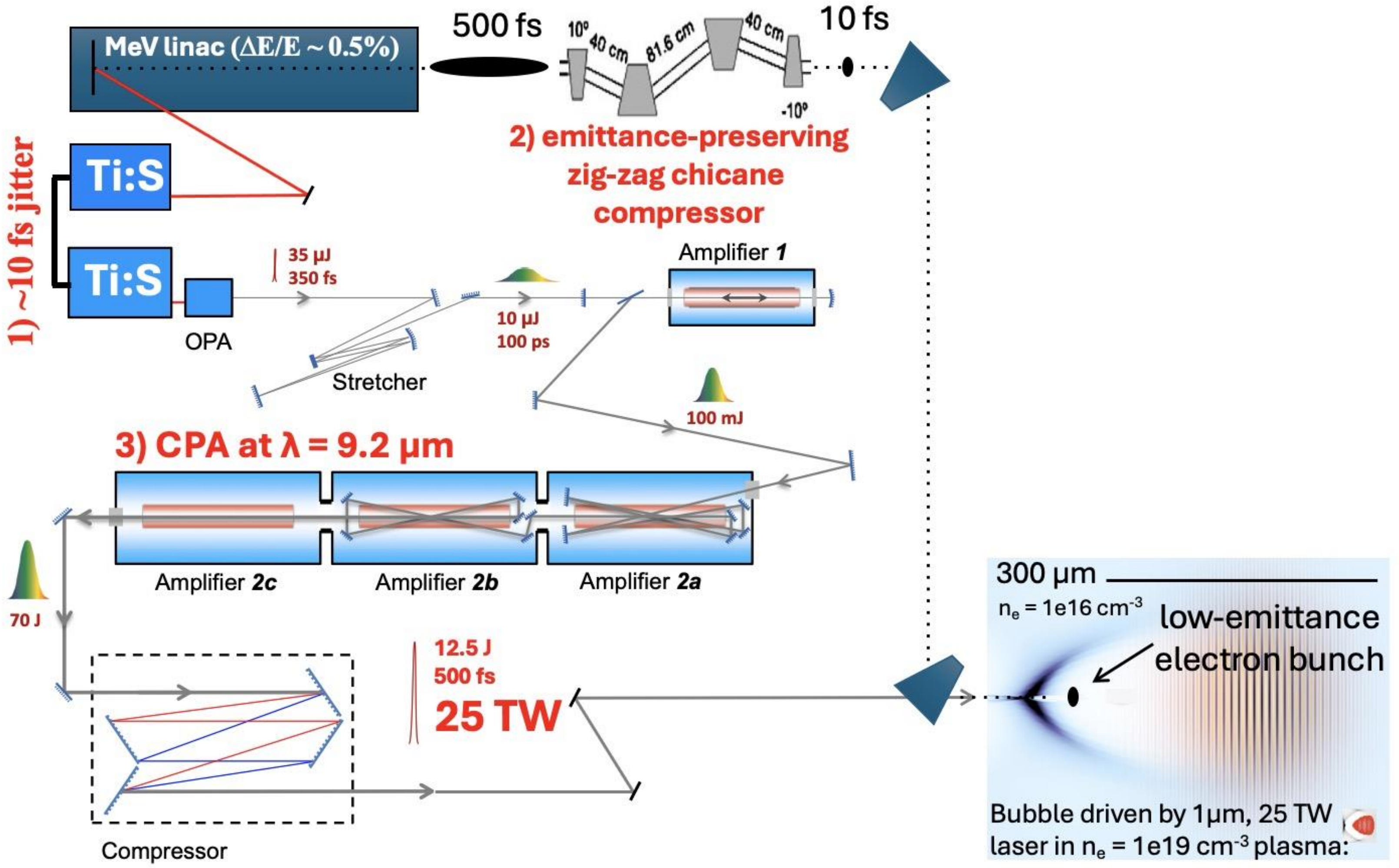
New capabilities:
- CO_2 laser: >10 J, 2 ps, > 5 TW
- linac e-beam probe synchronized, compressed to fs level?
- optical diagnostic system expanded and tested

1st generation CO_2 LWFA experiment with external injection

Dream parameters:

1) 10 fs laser-e-beam rms jitter
2) e-bunch compression to 10 fs
3) 25 TW CO_2 pulse

Actual parameters will depend on status of laser and linac development.



SUMMARY

Year 1-2 goals:

1) Explore low-n_e, high-P_L limits of self-injected CO_2-LWFA

- use current (or slightly upgraded) CO_2 laser parameters

2) Strengthen optical wake diagnostics for $n_e \sim 10^{16}$ cm^{-3} plasma

- add transverse CTS, Faraday probes; MIR harmonics of CO_2 drive pulse.

3) Simulate energy-spread, emittance growth in low-n_e wakes

- relate ΔE, ε_n growth to laser and plasma input parameters
- use maching-learning algorithms to hasten search for optimum

Year 3 goal:

1) 1st generation externally-injected CO_2-LWFA experiment.

- take advantage of CO_2 power upgrades & e-beam synchronization/compression advances
- leverages Navid's work in developing e-beam probes
- a preparatory "Mercury" mission to build experience for a future "Apollo" moon-landing mission

CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	*n/a*
	Peak Power	GW	~3		*n/a*
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	M^2	---	~1.5		
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	
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	5	*~5 TW operation will become available shortly into this year's experimental run period. A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	*initially ~5, higher by year 3.*
	Pulse Mode	---	Single		*single*
	Pulse Length	ps	2		*2 ps or shorter*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	*initially 5-10, higher by year 3*
	M^2	---	~2		*~2*
	Repetition Rate	Hz	0.05		*best available*
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*	*Linear*

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*	*50-65 (year 3 only)*
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	*adjust for shortest length & lowest emittance (yr 3 only)*
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*	*~100 fs or shorter, depending on developments by yr 3.*
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.*	*~ 30 μm; exact value will depend on results of yr 1-2 research*
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	*as low as achievable*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	*match CO2 laser rep. rate*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	*single bunch*

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 are presently available and setup to deliver Stage II parameters should be complete during FY22*	*800 nm*
FWHM Bandwidth	nm	20	13		*13 nm*
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.*	*75 fs*
Chirped FWHM Pulse Width	ps	≥50	≥50		*50 ps*
Chirped Energy	mJ	10	200		*10 mJ*
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.*	*7 mJ*
Energy to Experiments	mJ	>4.9	>80		*5 mJ*
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*	*532 nm*
Energy	mJ	0.5		*0.5 mJ*
Pulse Width	ps	10		*2-3 ps*

Experimental Time Request

CY2024 Time Request

Capability	Setup Hours	Running Hours
Electron Beam	0	0
NIR Laser	60	140
LWIR Laser	60	140

Total Time Request for the 3-year Experiment (including CY2024-26)

Capability	Setup Hours	Running Hours
Electron Beam	60 (yr 3 only)	140 (yr 3 only)
NIR Laser	180	420
LWIR Laser	180	420

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.: best possible compression and synchronization with CO2 laser (yr 3)
- CO_2 Laser
  - Please note any specialty laser configurations required here: polarization control, harmonics of split-off portions of beam generated in e.g. $AgGaSe_2$
- Ti:Sapphire and Nd:YAG Lasers
  - Please note any specialty non-CO_2 laser configurations required here: compressed Ti:S pulse at LWFA chamber
- Hazards & Special Installation Requirements
  - Large installation (chamber, insertion device, etc.): no
  - Cryogens: no
  - Introducing new magnetic elements: Spectrometer magnet, < 1 T
  - Introducing new materials into the beam path: no
  - Any other foreseeable beam line modifications: compressor for e-beam (yr 3)