Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

25th Annual

Accelerator Test Facility (ATF) Users' Meeting

NP-312796: Two-color Injection of Bright Electron Beams

N. Vafaei-Najafabadi[1,2*], W. Li[1], I. Petrushina[2], R. Zgadzaj[3], M. Downer[3], A. Gaikwad[2], B. Romasky[2], E. Trommer[2], A. Cheng[2], R. Samulyak[2], A. Farrell[4], C. Zhang[4], Y. Wu[4], C. Joshi[4], M. Babzien[1], M. Polyanskiy[1], I. Pogorelsky[1], M. Palmer[1]

[1]Brookhaven National Laboratory, [2]Stony Brook University,

[3]University of Texas at Austin, [4]UCLA, *PI

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Accelerator Facilities Division

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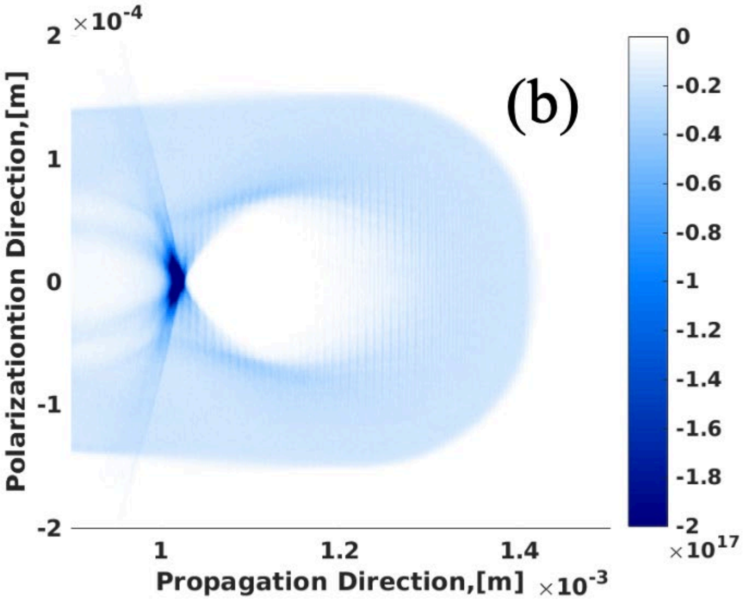
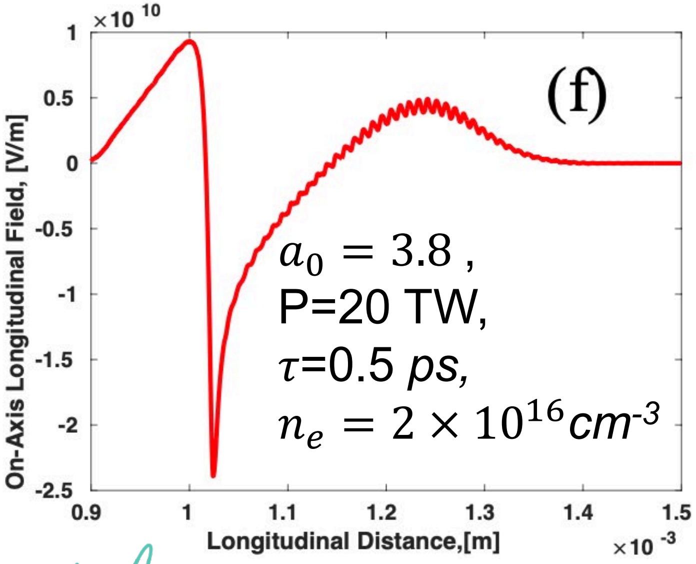
P. Kumar, Physics of Plasmas, 28, 013102 (2021)

LWIR-driven laser wakefield acceleration

- A laser driver with $a_0 \sim 4$ creates fully blown out LWFA in the "bubble regime"
- Strength of ponderomotive force scales with $\sqrt{I\lambda^2}$, so LWIR drivers can reach $a_0 \sim 4$ with modest intensities (at ~20 TW power)
- $a_0 \sim 4$ can be reached by and LWIR laser without triggering self-injection in LWFA*
- Bubble created by LWIR driver can be >100 μm, providing the ability for precise alignment of multiple beams with respect to the bubble

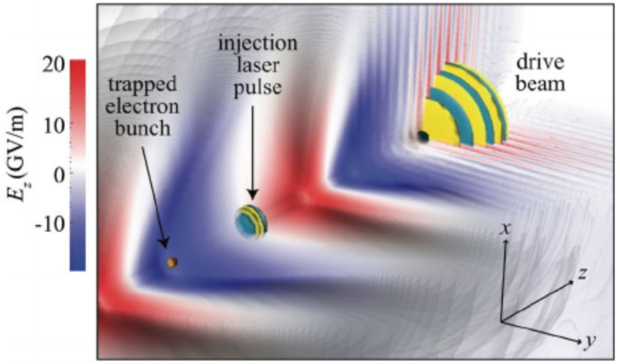




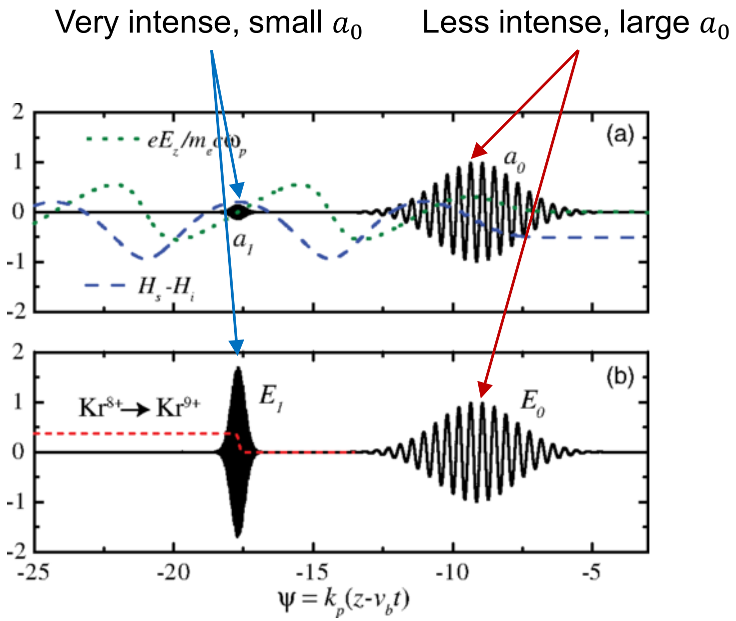
* See A. Jain, Proceedings of AAC 2022

Two-color ionization injection

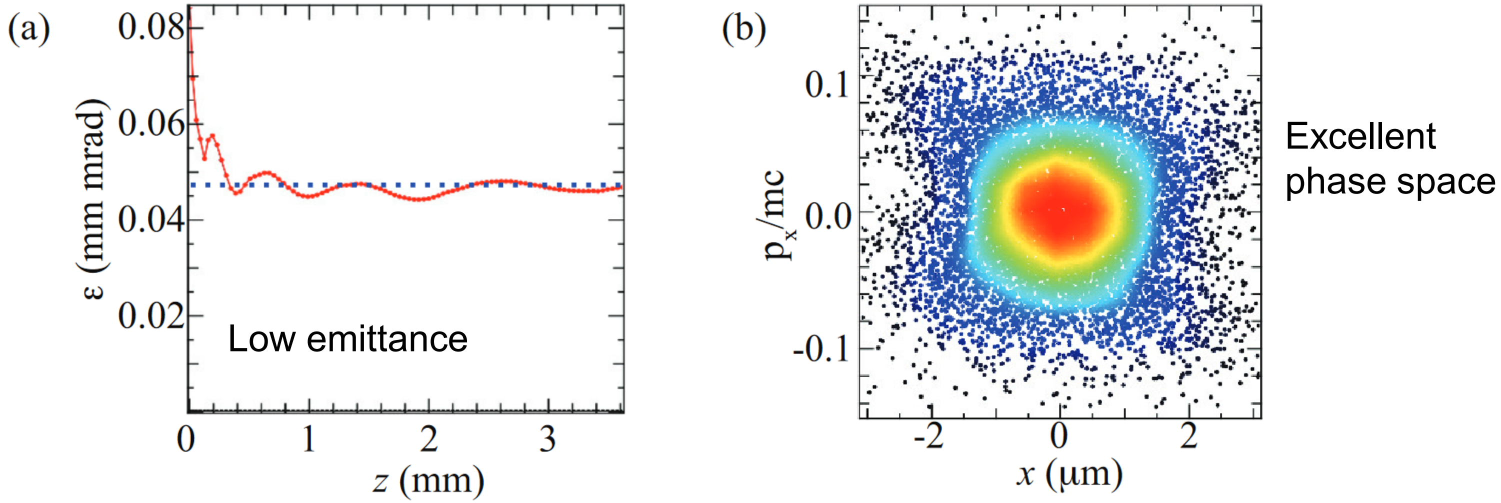
- A second laser can trigger ionization injection in the wakefield driven by the LWIR laser, creating a high-quality beam
- Drive laser needs large a_0 to form plasma wakefield, but we want low I to avoid prematurely ionizing the gas
- Injector laser needs high I to ionize the gas, but low a_0 to avoid disturbing the plasma
- ATF is ideally suited for this experiment:
  ATF CO_2 :driver
  ATF Ti:Sapphire: injector



Schroeder, *PRSTAB* **17**, 101301 (2014)



Yu, *PRL* **112**, 125001 (2014)



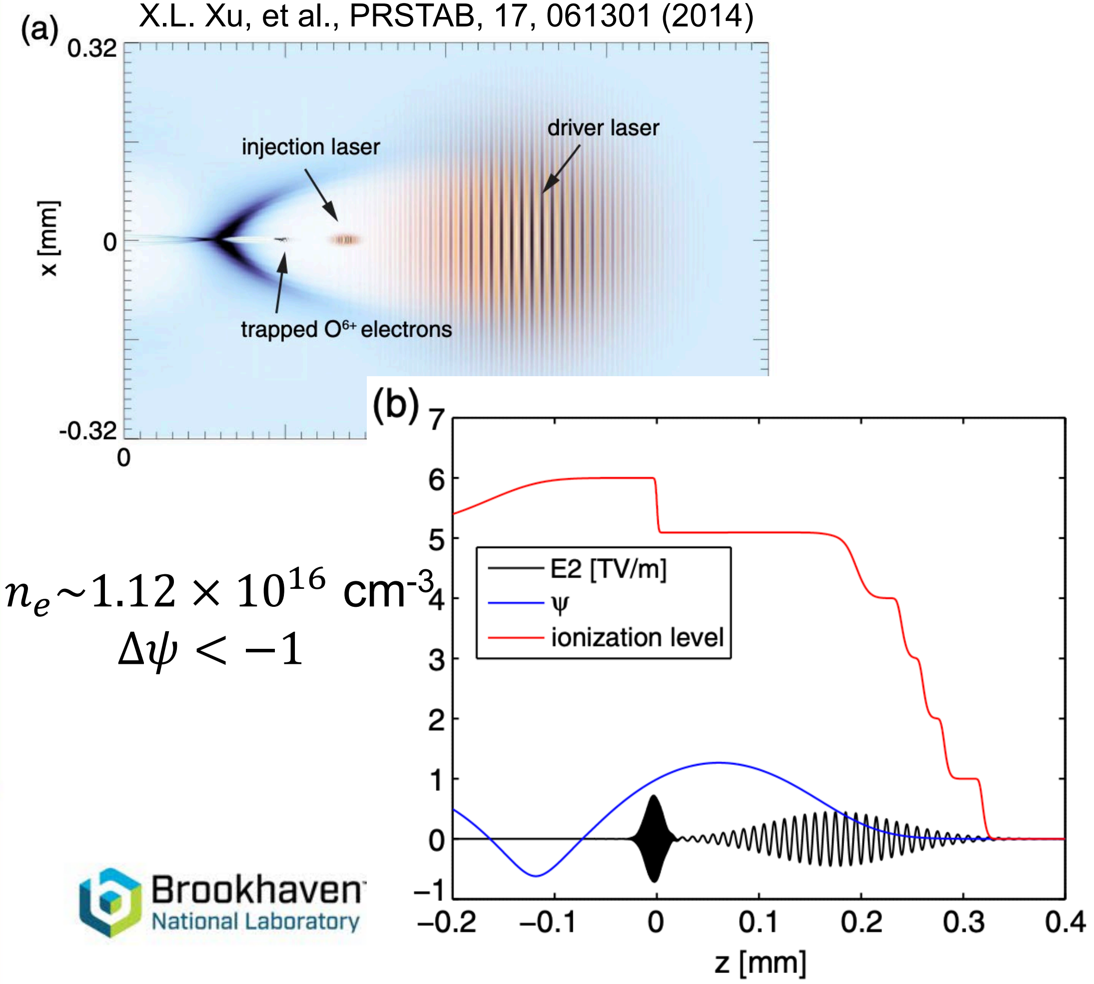
Schroeder, *European Conference on Lasers and Electro-Optics* (2015)

Trapping condition for electrons

Ideal Trapping Scenario

P~20 TW $\tau \leq 0.5$ **ps**

X.L. Xu, et al., PRSTAB, 17, 061301 (2014)

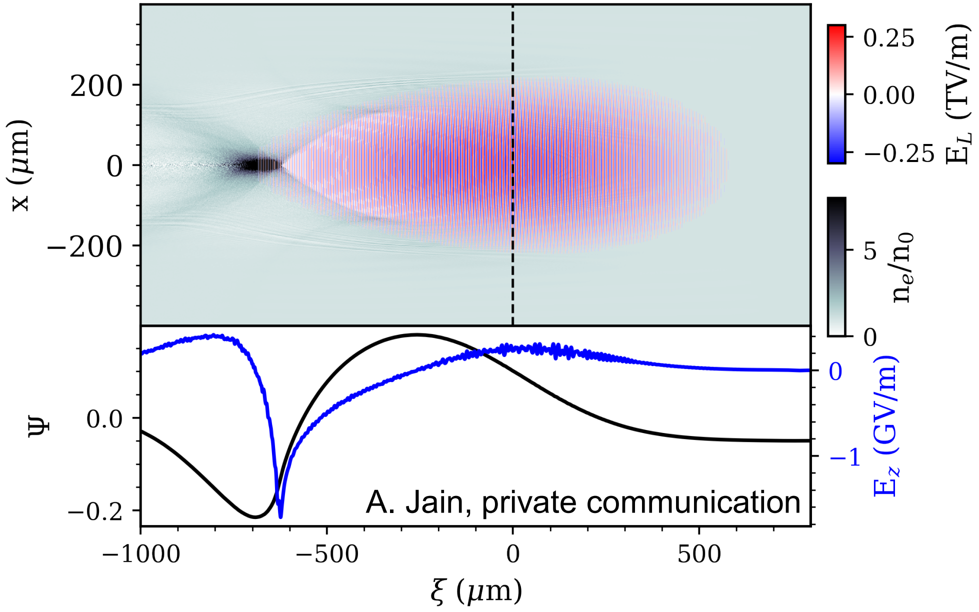


$n_e \sim 1.12 \times 10^{16}$ cm^{-3}

$\Delta\psi < -1$

Current Scenario

P~5 TW $\tau \approx 2$ **ps**



$z = 4.5$ mm

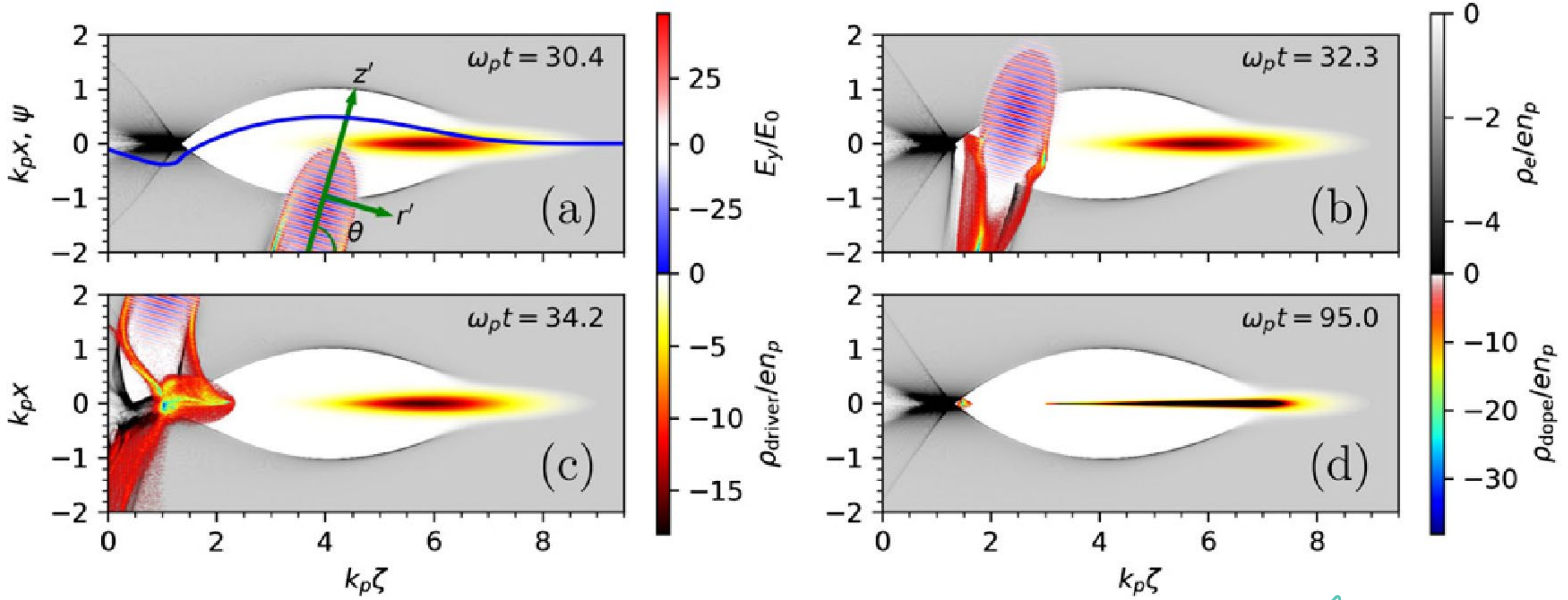
$n_e < 1 \times 10^{15}$ cm^{-3} : to create a bubble larger than the laser

$\Delta\psi < -0.4$: too small for trapping

Ionization Injection with Current Laser Config

Ponderomotive assistance

- We can use the injector laser to help!
- Ponderomotive force of injector laser at oblique angle accelerates the ionized electrons
- The electrons have an initial momentum, lowering the necessary trapping potential



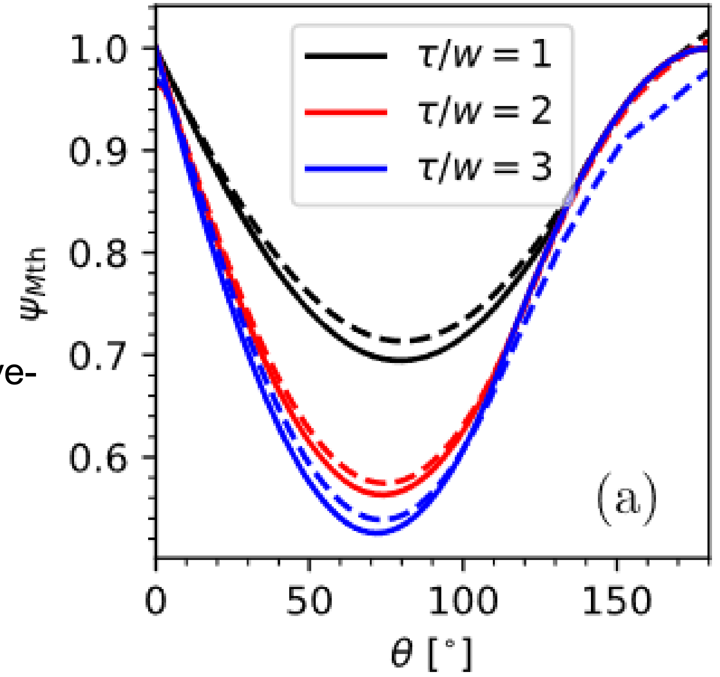
Zeng, *New J. Phys*. **22**, 123003 (2020)

Note: driver is an e-beam, but the physics of injection is the same

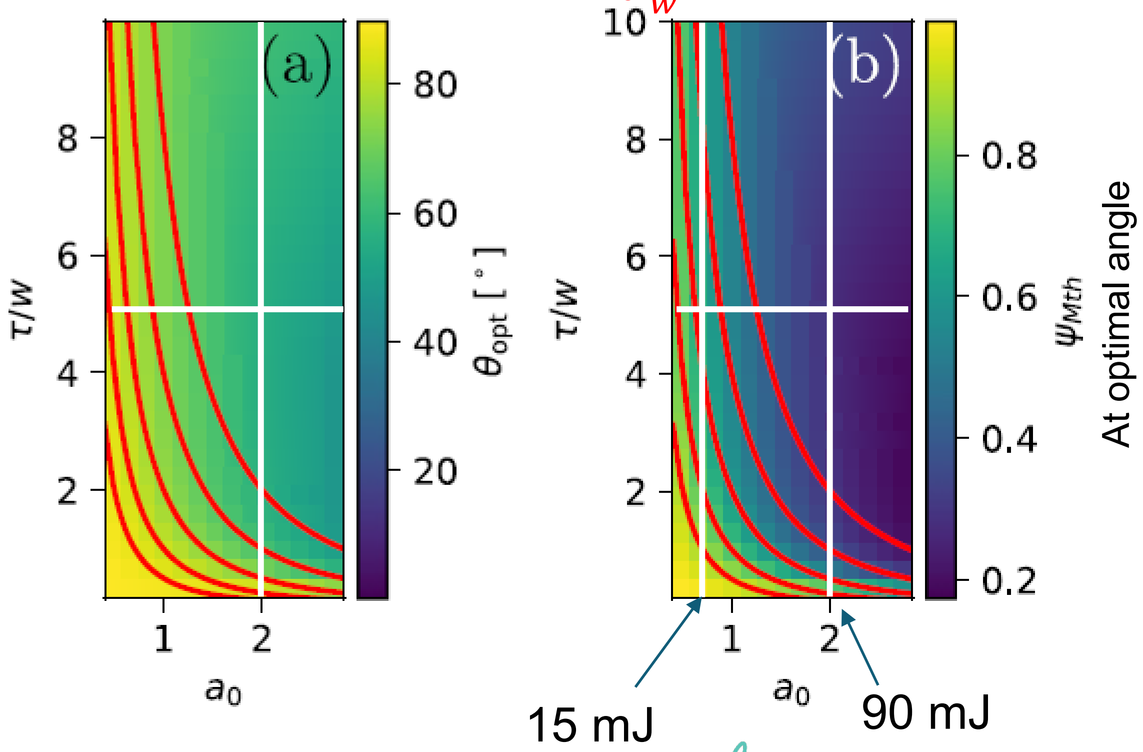
Ponderomotive assistance parameters

- Trapping threshold depends strongly on angle of incidence
- Optimal angle of incidence and magnitude of trapping threshold dependent on a_0 and $\frac{\tau}{w}$, the laser aspect ratio

Trapping threshold as fraction of ponderomotive-free trapping threshold



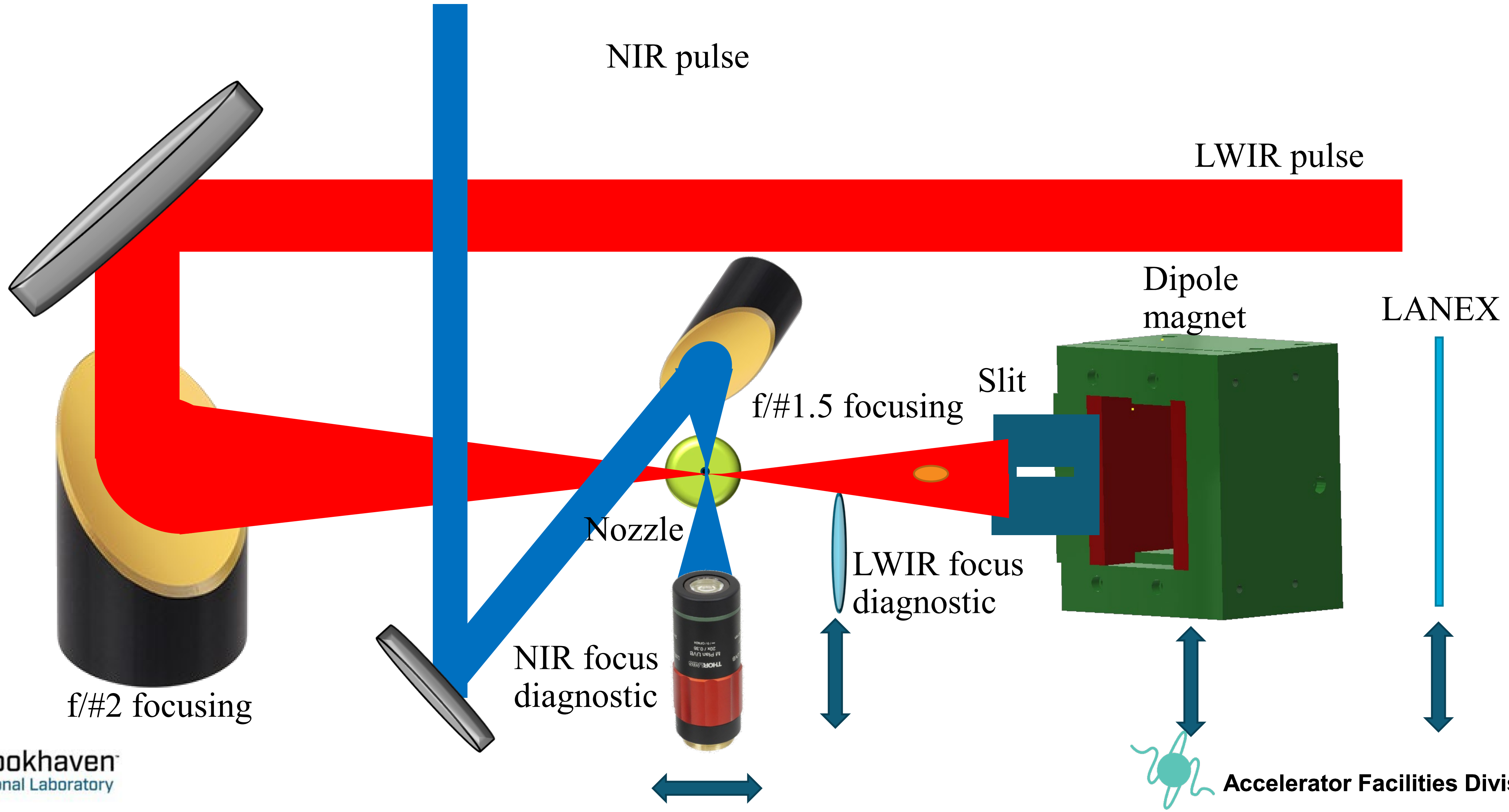
Contours of constant $a_0^2 \frac{\tau}{w}$: 0.5, 1, 2, 4, 8



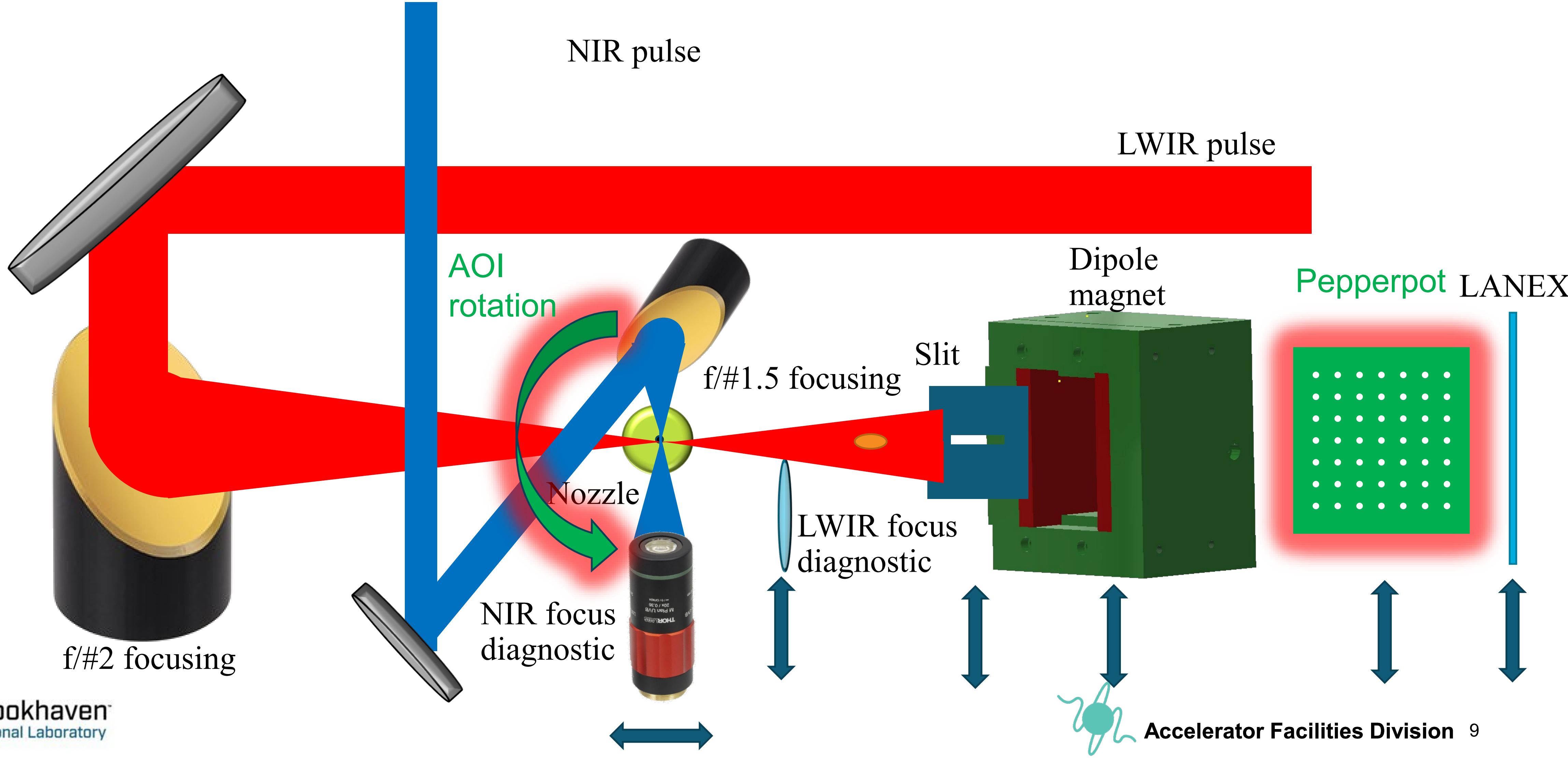
For ATF, f/1.5 focusing, $a_0 \cong 0.7$(at 15 mJ), $\frac{\tau}{w} \cong 5$

Zeng, *New J. Phys.* **22**, 123003 (2020)

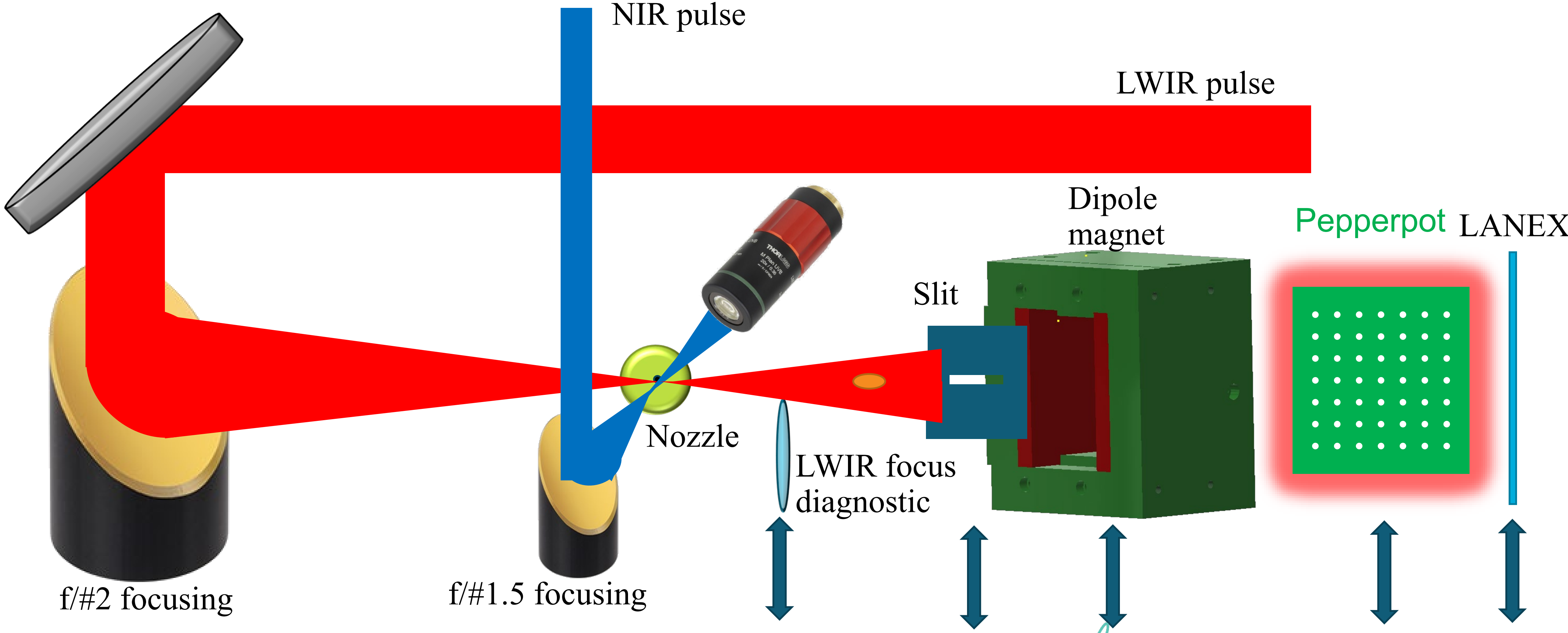
Experimental setup (inherited from AE88)



Experimental setup (new modifications)

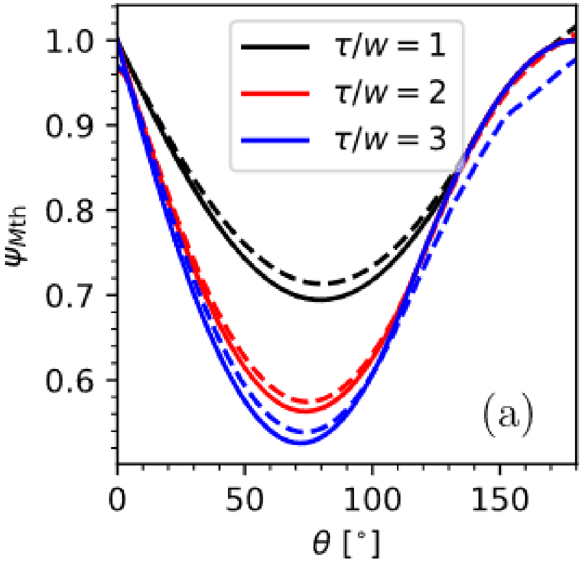


Experimental setup (new modifications)

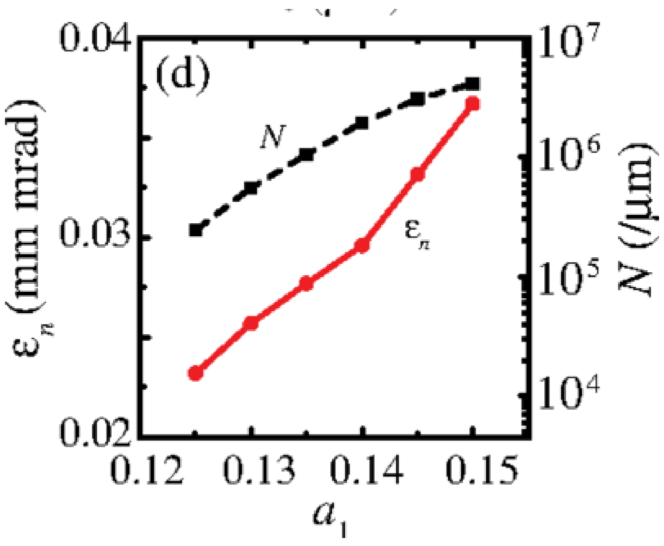


Proposed measurements

- Measure dependence of yield on angle of incidence, drive laser intensity, and injector laser intensity: confirmation that ponderomotive assistance is occurring
- Measure dependence of emittance on angle of incidence, drive laser intensity, and injector laser intensity: confirmation of beam quality and finding optimal beam brightness



Zeng, *New J. Phys.* **22**, 123003 (2020)

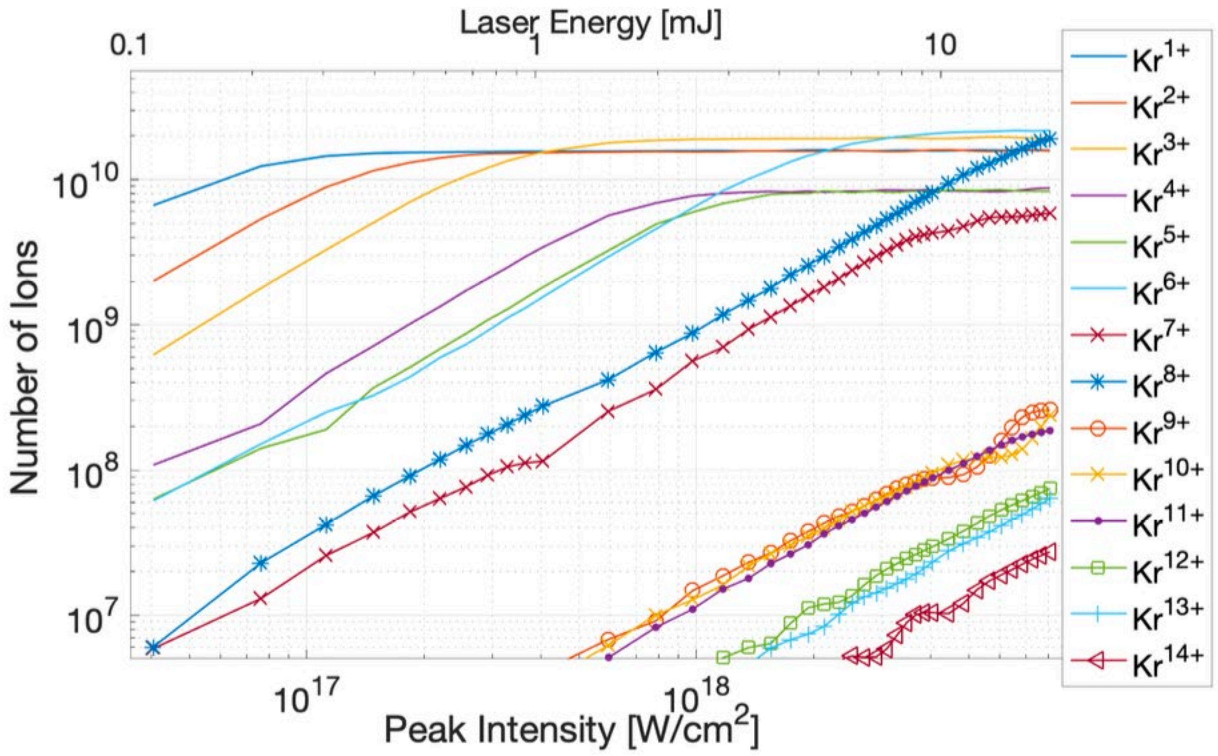


Yu, *PRL* **112**, 125001 (2014)

Expected experimental parameters

- Expected gradient >1 GeV/m = 1 MeV/mm
- Expected electron energy 5-10 MeV (~5 mm gas jet)
- Expected electron emittance <1 mm-mrad (number obtained in Zeng, New J. Phys. 22, 123003, 2020 simulation)
- High levels of Kr ionization is expected

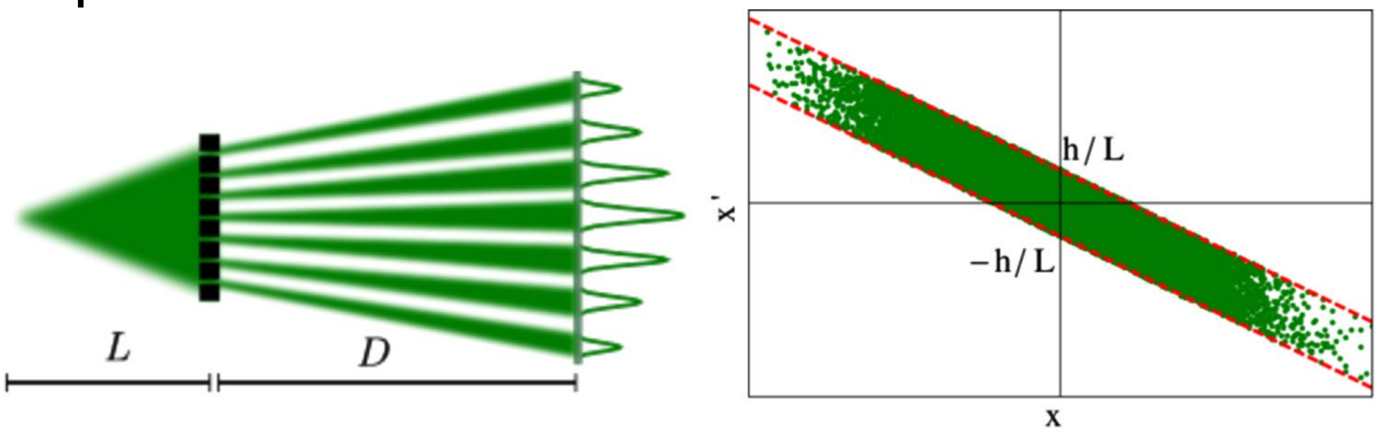
Ionization of Krypton



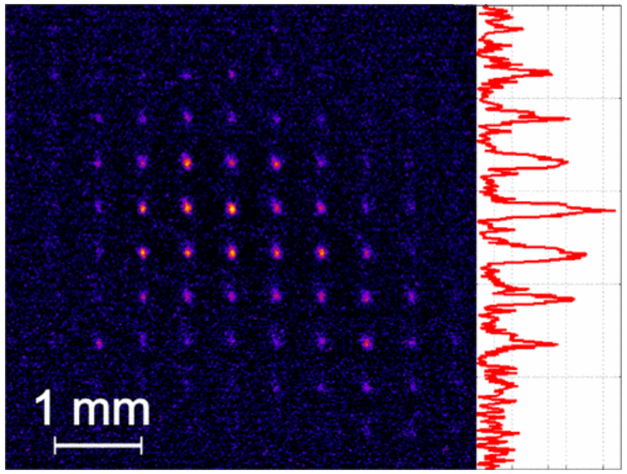
N. Vafaei-Najafabadi, Proceedings of AAC 2022

Emittance measurement

- Need a single-shot measurement due to shot-to-shot fluctuations
- Pepperpot is well-established method used in previous LWFA experiments
- Intercept beam with a grid of holes and measure the size, shape, and spacing between the transmitted beamlets to retrieve transverse phase space

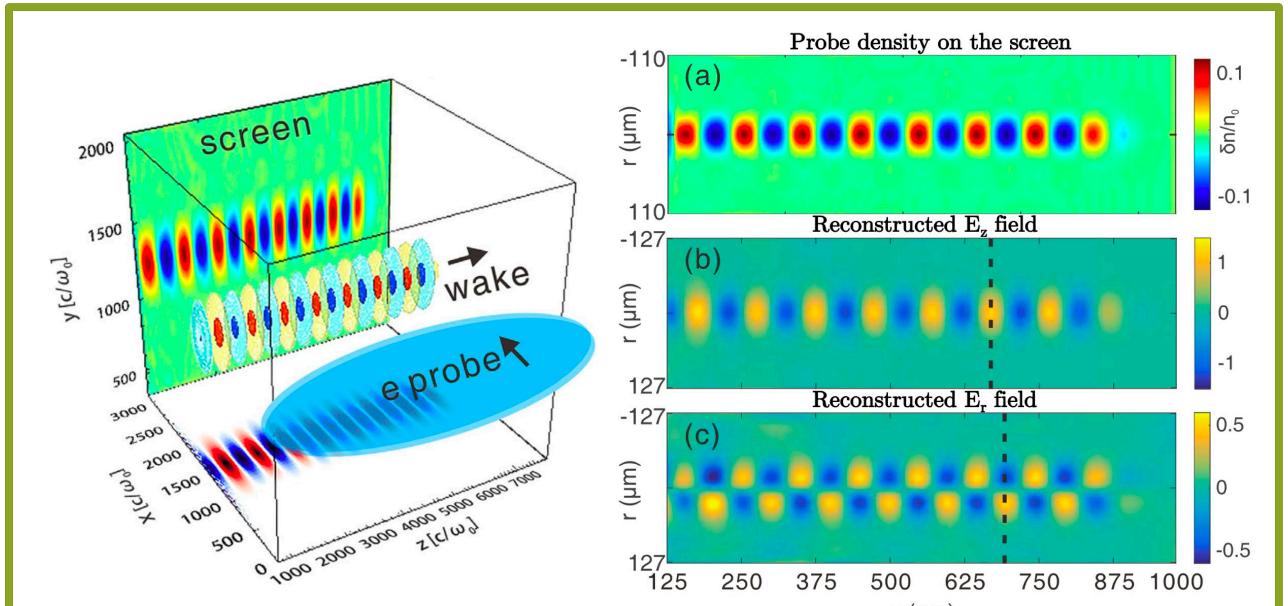


Manahan, *New J. Phys.* **16**, 103006 (2014)

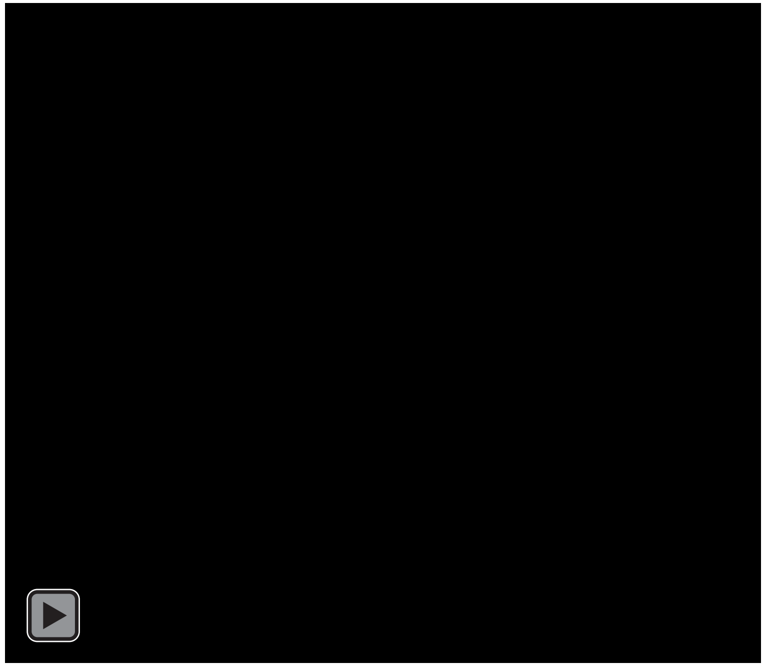


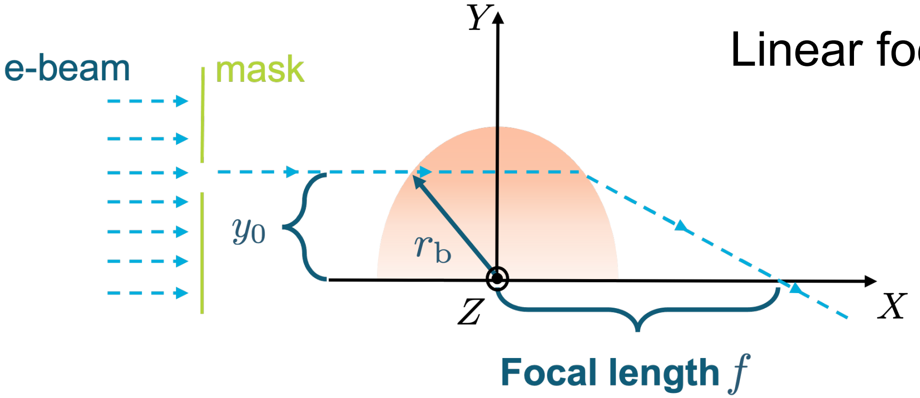
Brunetti, *Phys. Rev. Lett.* **105**, 215007 (2010)

Optional: Electron Beam as Probe



C.J. Zhang et al., Scientific Reports 6:29485 | DOI: 10.1038/srep29485





Linear focusing force in a bubble: $F_r = kr$ (wakefield theory suggests $k \approx 0.5$)

- For 1×10^{15} cm^{-3}, focal length is ~3 cm
- Both lasers can drive plasma waves, allowing for precise alignment between the laser pulses

Conclusion

- Two-color ionization injection has been shown in simulation to produce high quality electron beams
- Ponderomotively assisted injection allows us to conduct the first two-color ionization injection experiments with the potential for low-emittance beam generation
- Stepping stone towards producing ultra-low emittance, high brightness beams in a colinear configuration after ATF CO_2 upgrades to >15 TW

Backup slides

Slides for Program Advisory Committee

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*	*nominal*
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	*nominal*
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*	*Max compression available*
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*
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	*1 um*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	*0.02 Hz (limited by CO2)*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	*Single Mode*

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*	
	Peak Power	GW	~3		
	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.*	*>5*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		2 (phase I) <1 (phase II)
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	5
	M^2	---	~2		
	Repetition Rate	Hz	0.05		*0.05*
	Polarization		Linear	*Adjustable linear polarization along with circular*	*linear*

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
FWHM Bandwidth	nm	20	13		
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.*	60
Chirped FWHM Pulse Width	ps	≥50	≥50		
Chirped Energy	mJ	10	200		
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.*	90
Energy to Experiments	mJ	>4.9	>80		
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*	
Energy	mJ	0.5		
Pulse Width	ps	10		

Special Equipment Requirements and Hazards

- CO_2 Laser
  - No specialty configurations required.
- Ti:Sapphire and Nd:YAG Lasers
  - No specialty configurations required.
- Hazards & Special Installation Requirements
  - We will require the installation of a 3.6 kG dipole spectrometer in the experimental chamber.

Experimental Time Request

CY2023 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)	40	80
Laser* + Electron Beam		

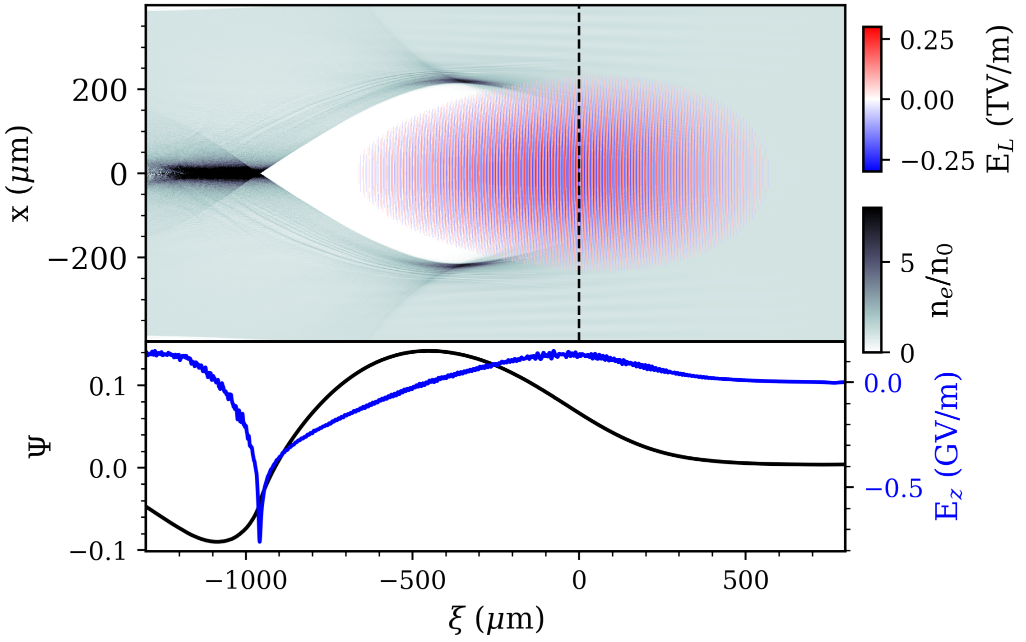
Total Time Request for the 3-year Experiment (including CY2023-25)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)	120	240
Laser* + Electron Beam		

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

Ponderomotive assistance at ATF

Low density gas: CO_2 laser strong enough to be [redacted]
$\Psi \cong 0.2$, not quite enough to trap electrons



$z = 4.8$ mm

$Power = 5\ TW$, $a_0 = 3.56$, $w_0 = 40\ \mu m$, $\tau_{FWHM} = 2$ ps, $\boldsymbol{n_0 = 3 \times 10^{14}\ cm^{-3}}$, $z_0 = 0\ \mu m$, $z_f = 2.2$ mm

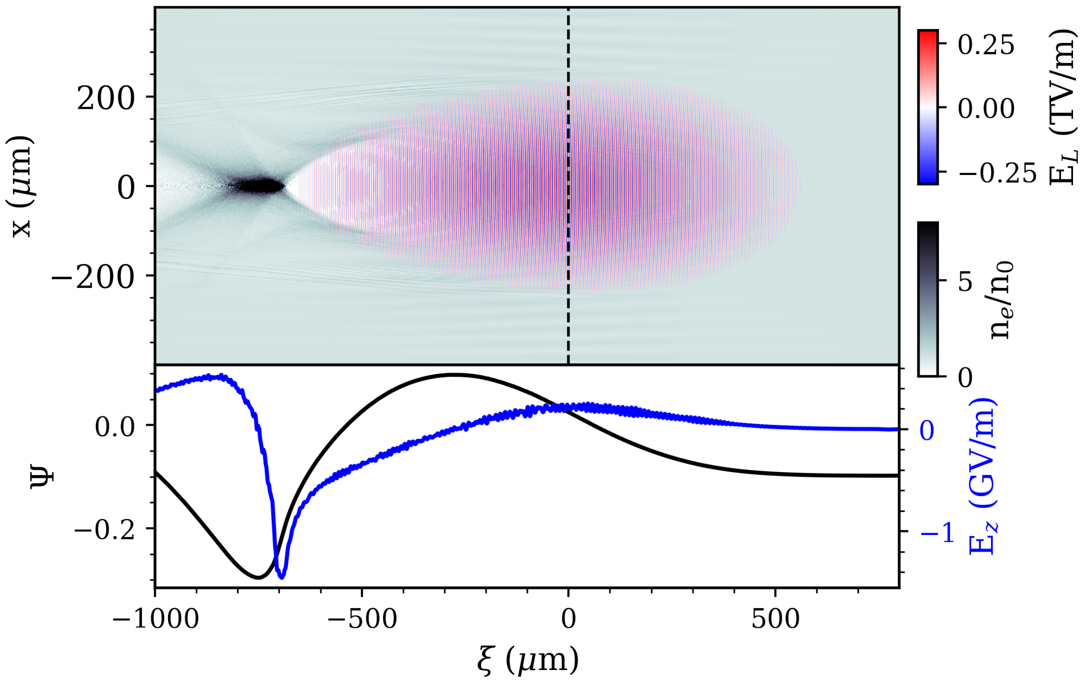
Higher density

3x higher density: CO_2 laser starts to become self-modulated

$\Psi \cong 0.5$, close to the trapping threshold

Critically, there is space at the back of the bubble for [redacted]

Current ATF laser parameters sufficient for ponderon[redacted]



$Power = 5\,TW$, $a_0 = 3.56$, $w_0 = 40\,\mu m$, $\tau_{FWHM} = 2$ ps, $\boldsymbol{n_0 = 1 \times 10^{15}\,cm^{-3}}$, $z_0 = 0\,\mu m$, $z_f = 2.2$ mm

Ti:sapphire parameters

$$E = 15 \text{ mJ}$$
$$FWHM_t = 60 \text{ fs}$$
$w = \sigma_x \cong 1.5\ \mu\text{m}$ (f/1.5 focusing, conservative M^2 of 2)
$$\tau = c\sigma_t \cong 7.5\ \mu\text{m}$$
$$a_0 \cong 0.7$$
$$\frac{\tau}{w} \cong 5$$
$$a_0^2 \frac{\tau}{w} \cong 2.5$$