Project ID: NP-315766

Project Title: Ultrafast Electron Radiography of LWFA

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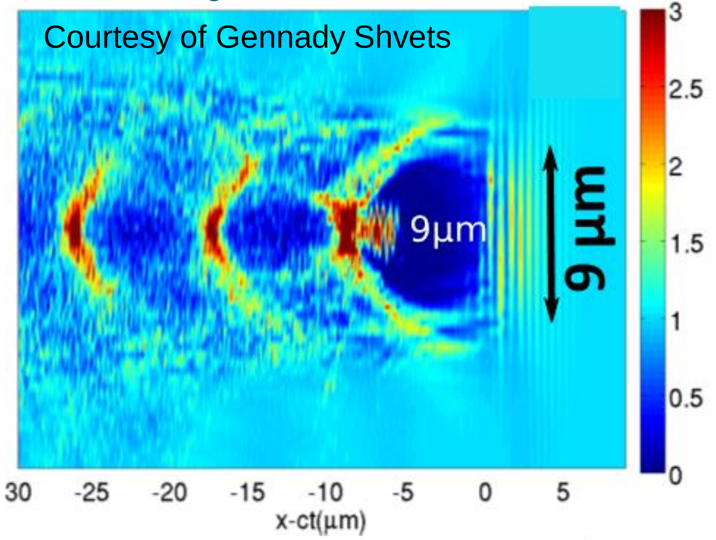
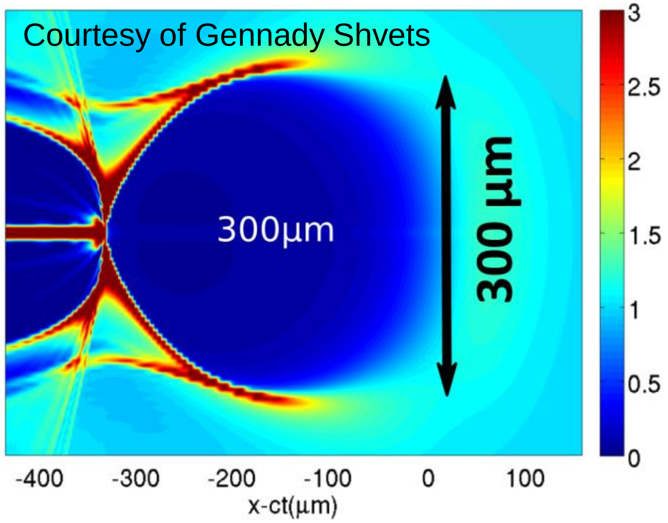
LWFA Using a Long-Wave Infrared (LWIR) Driver

CO_2 laser system: 2 ps pulses, up to 10 J energy, **wavelength ~10.2 um**

λ_{drive}= 0.8 um, 25 TW, 30 fs
n_e = 2e19 cm^{-3}



λ_{drive}= 10 um, 25 TW, 500 fs
n_e = 1e16 cm^{-3}



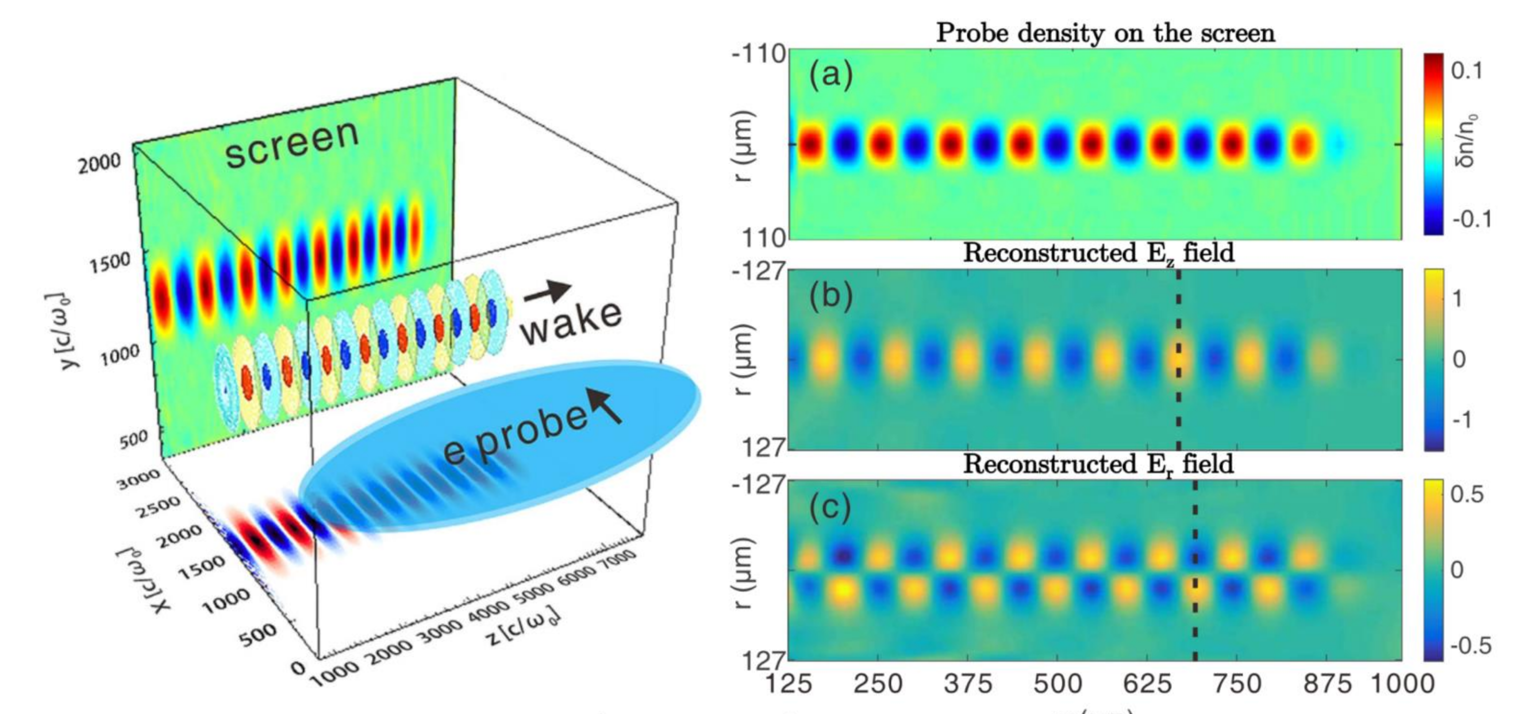
Precise and controllable external injection!

Diagnostic tools are needed to **characterize the fields** inside such structures and to **improve the means of external injection**.

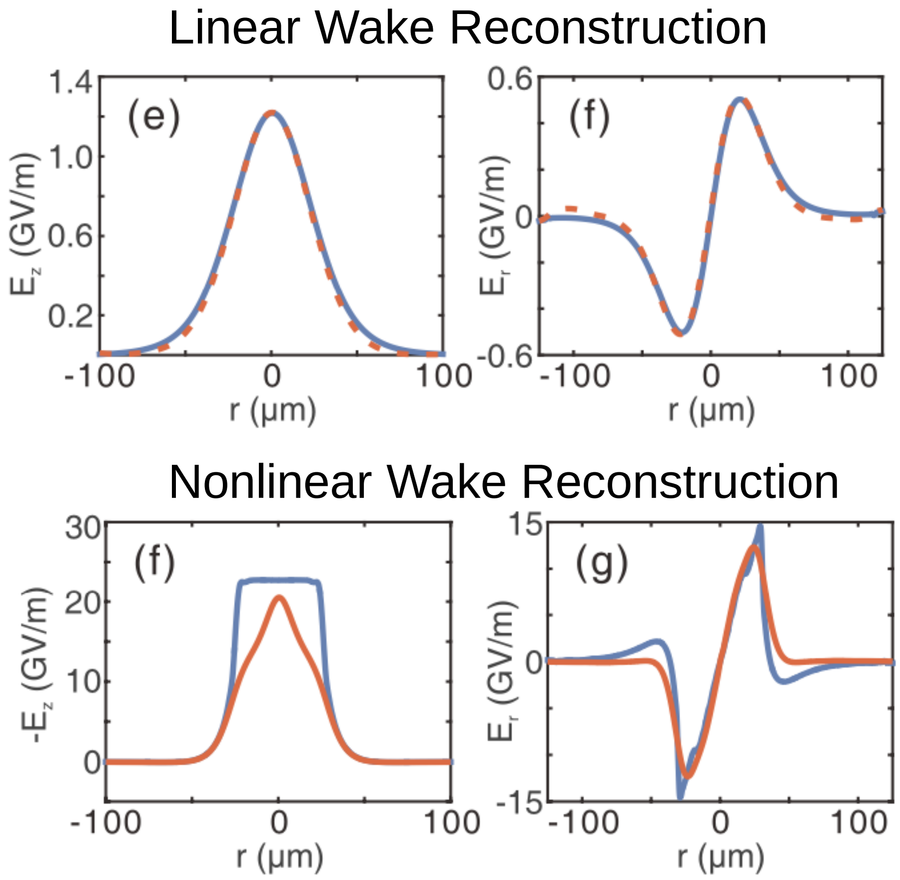
How is LWFA diagnostic usually done?

- Use **optical methods—**lasers.
- These methods **rely on the index of refraction** of plasma.
- **Optical methods** have been **extensively studied** and have **successfully demonstrated** the ability to capture **shadowgraphs** of the plasma wakes.
- **BUT: difficult at low plasma densities.**

Fluid-based formalism for electron probing of fields in LWFA developed in 2018



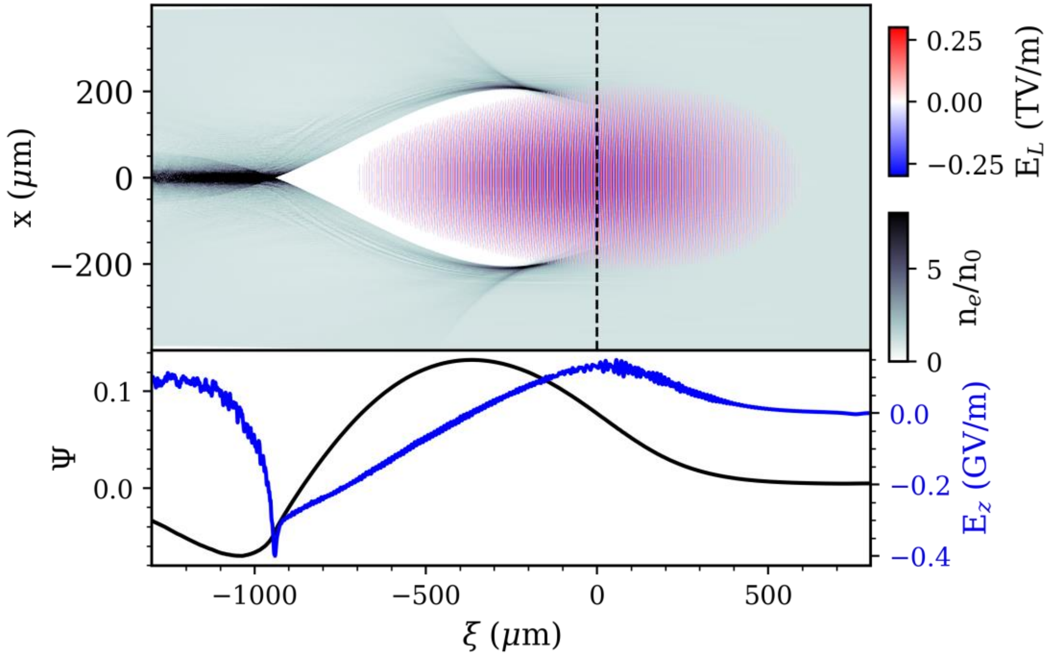
C.J. Zhang et al., Scientific Reports 6:29485 | DOI: 10.1038/srep29485



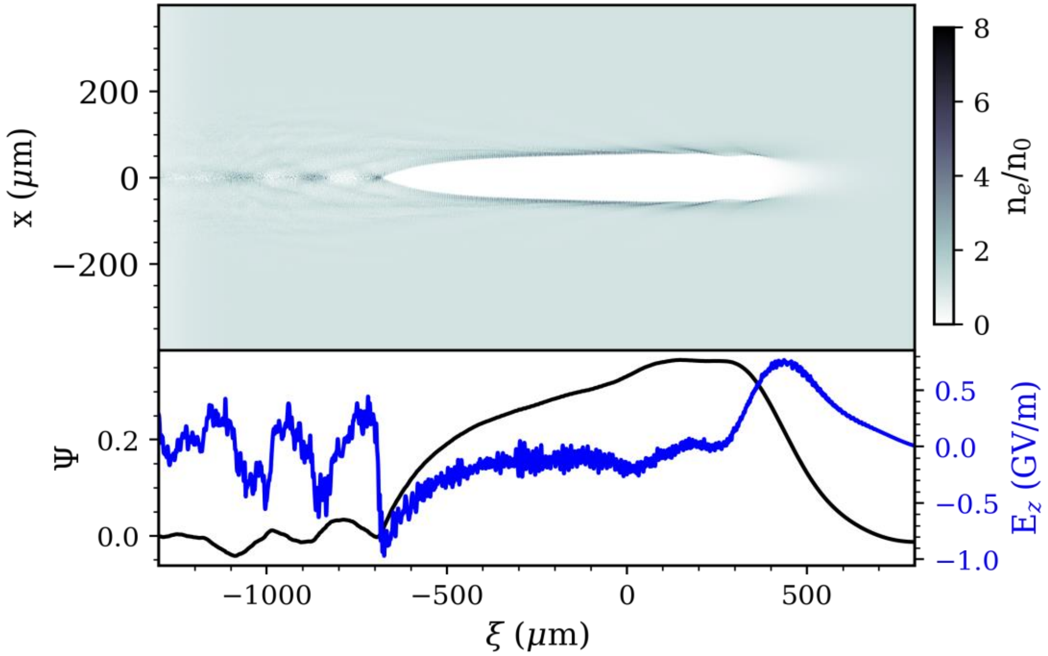
$$\vec{\theta}(y,z) = \int -\frac{e\vec{E}dx}{cp_0} \qquad \vec{d} = \vec{\theta}L \qquad \frac{\delta n}{n} = -\nabla \cdot \vec{d}$$

Fluid theory reconstruction works well in the linear regime, but not very well in the nonlinear regime

Expected Experimental Regimes with 5 TW Laser Pulse

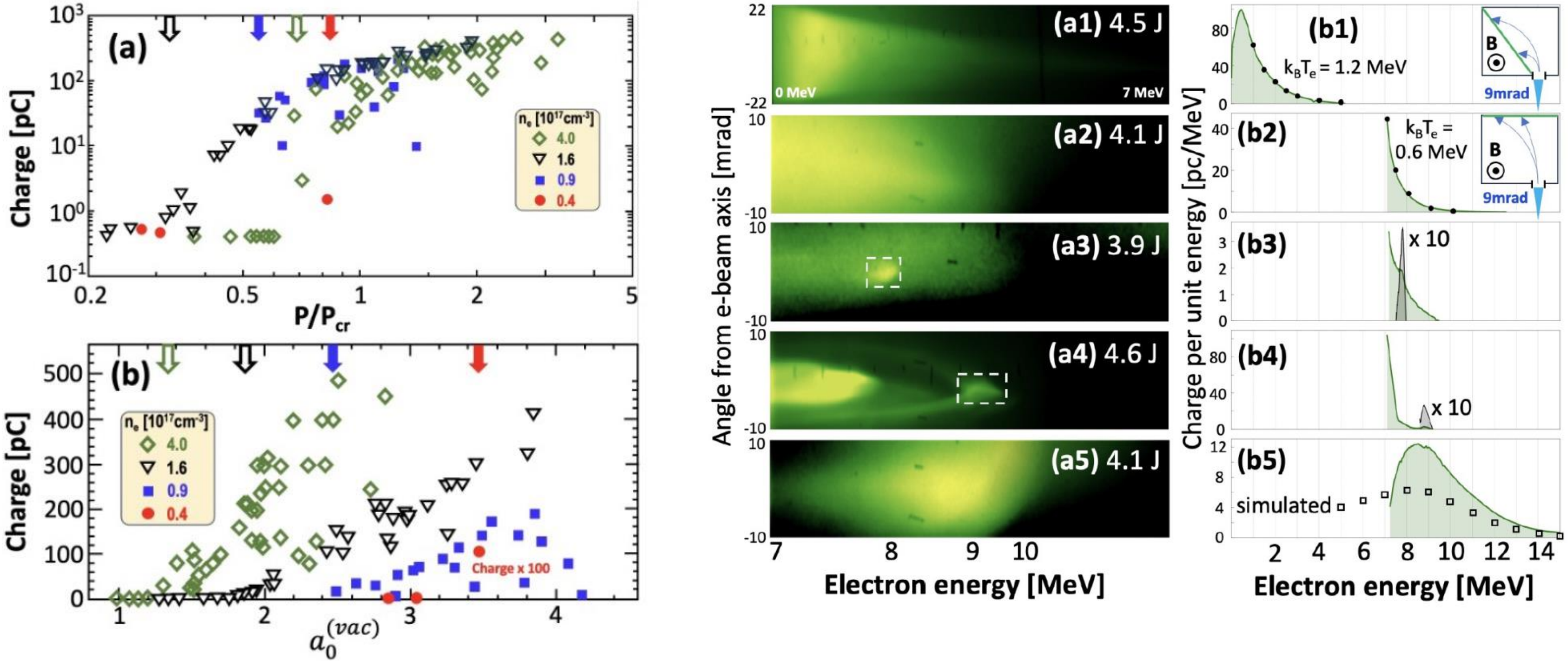


$n_e \sim 10^{14}\ \mathrm{cm}^{-3}$
"Classic" Blowout Regime
Primarily used in LWFA research at $1\mu m$
High acceleration and focusing fields
Structure radius ~ 200 μm



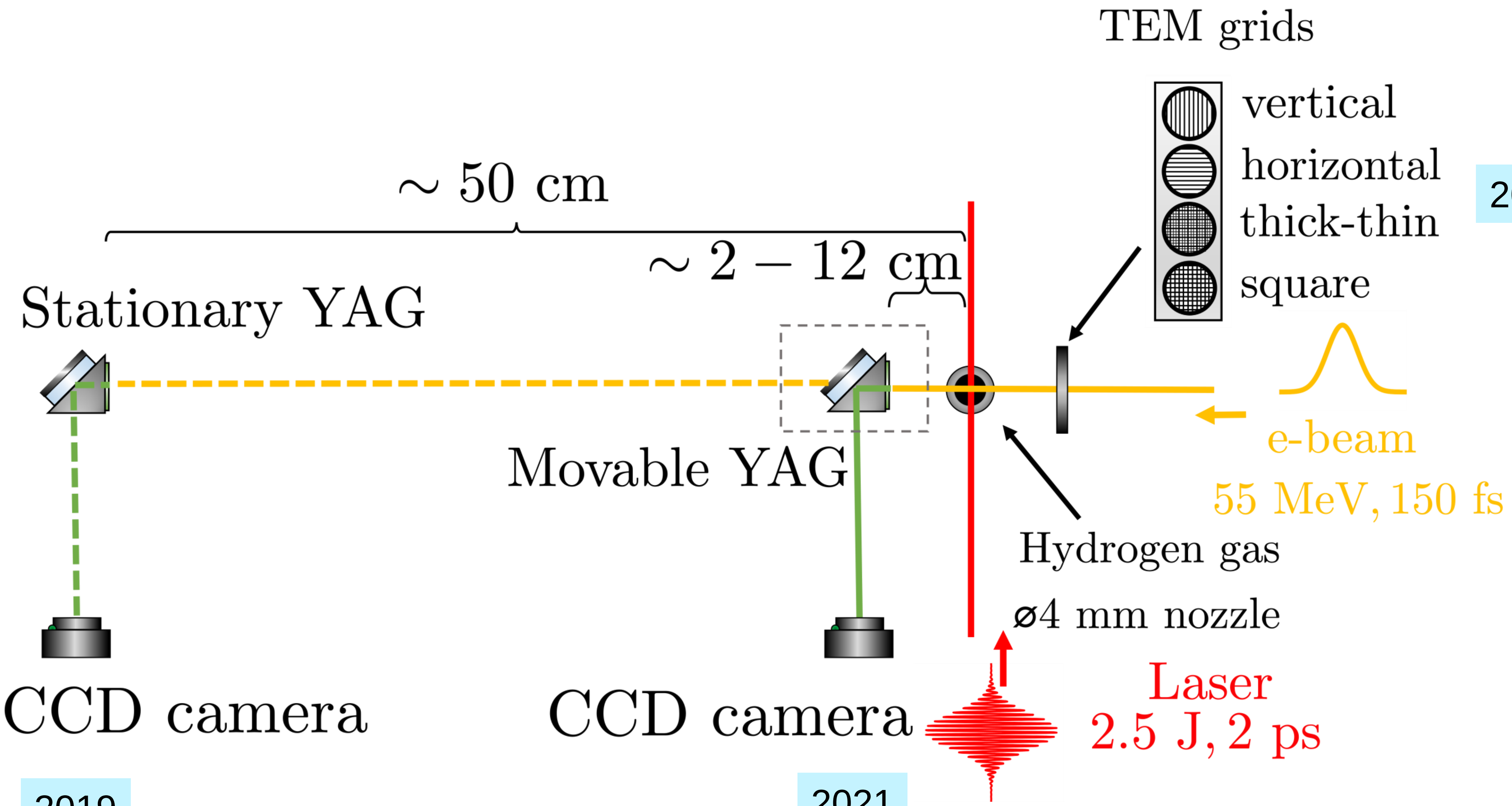
$n_e \sim 10^{16}\ \mathrm{cm}^{-3}$
"Wakeless" Blowout Regime ($E_z \sim 0$)
Onset of "Forced" LWFA
High focusing fields only
Structure radius ~ 50 μm

LWFA Using a Long-Wave Infrared (LWIR) Driver



- Previous results with 2 TW of power brought down the threshold of injection to $\leq 10^{17}$ cm^{-3}
- Experiments with the upgraded 5 TW of power are expected to produce electrons at even lower density, where the laser pulse length is on the order of 1-10 plasma periods
- This creates the opportunity to simultaneously diagnose the fields and the generated electrons in the range of 10^{16} cm^{-3}

Using Movable BPM as Diagnostics

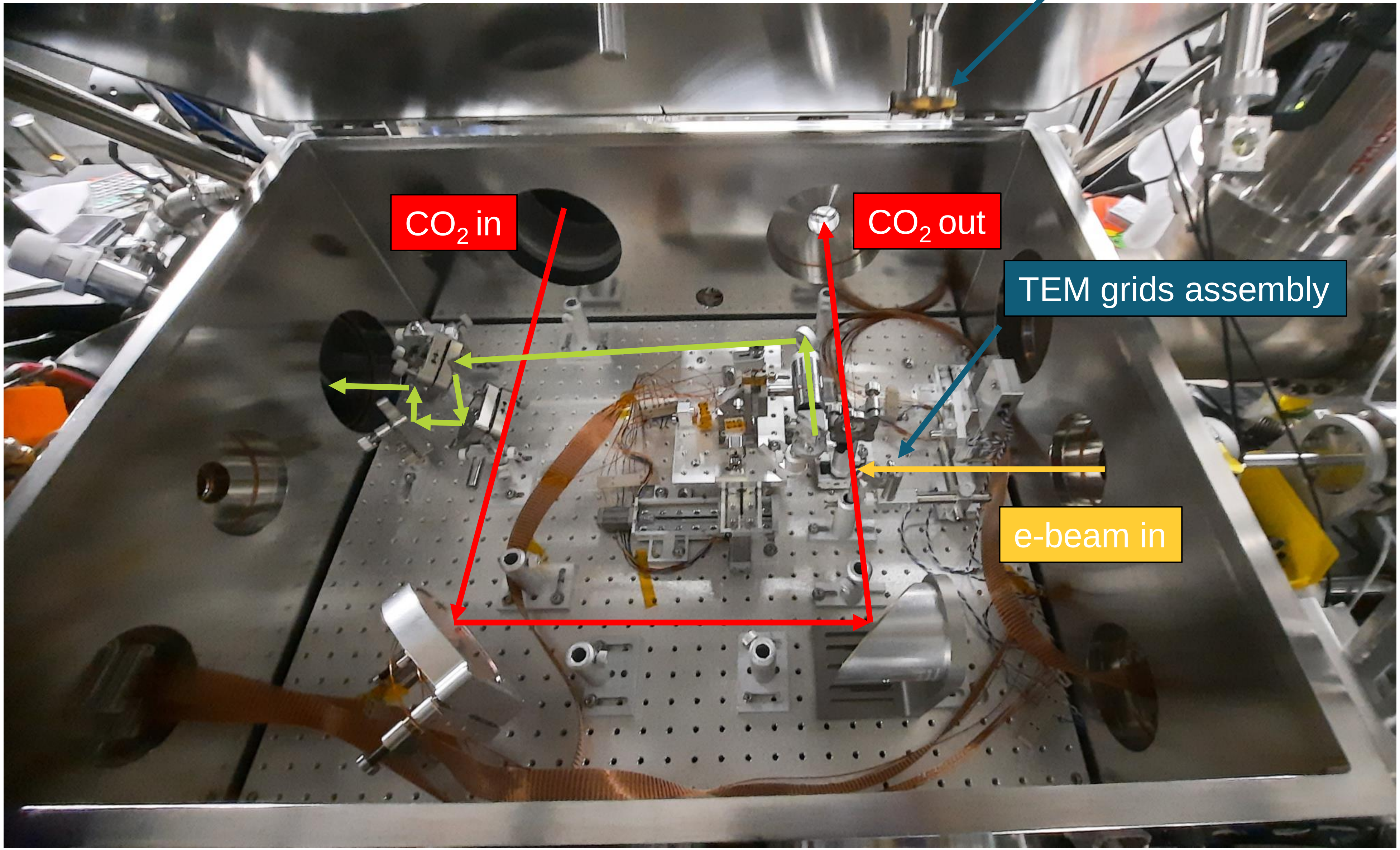


2022

2019

2021

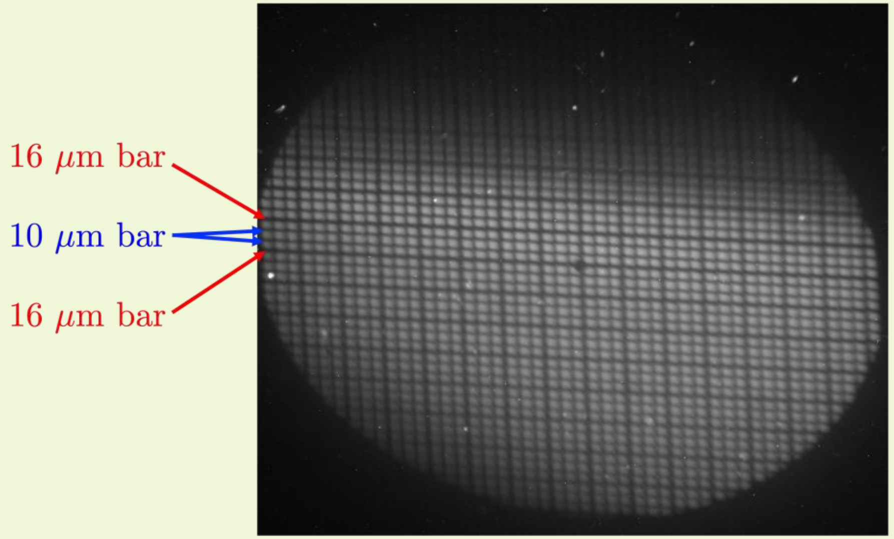
Experimental overview: LWFA chamber setup



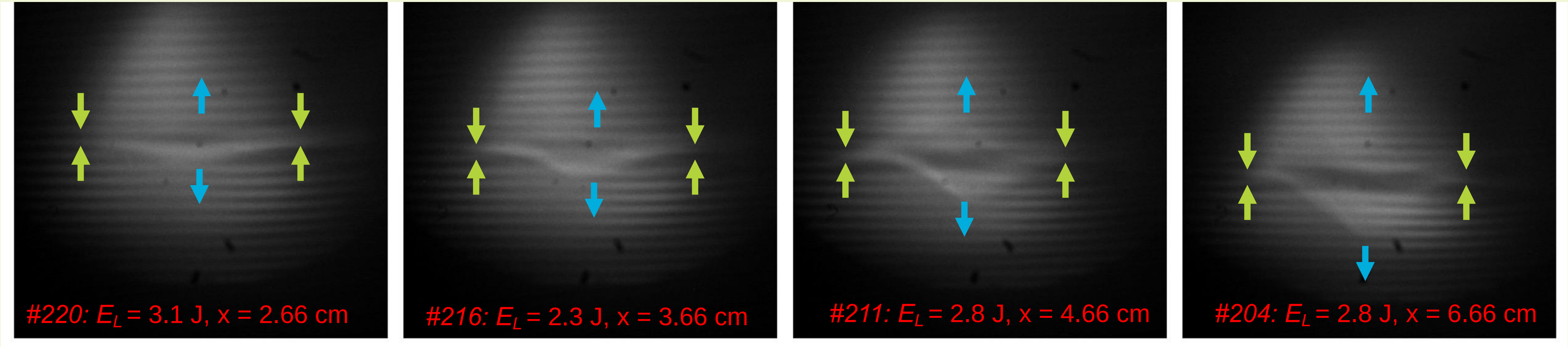
System Resolution of <10μm Demonstrated for Movable BPM

a) The resolution of the electron beam imaging system is well within the system requirement: measured vertical resolution 2.5±0.2 um/pxl, horizontal resolution 3.2±0.2 um/pxl.

b) A divergence-based emittance measurement technique utilizing the installed TEM grids and the movable YAG screen has been implemented. The data have been collected and analyzed to determine an upper limit on the transverse beam emittance.

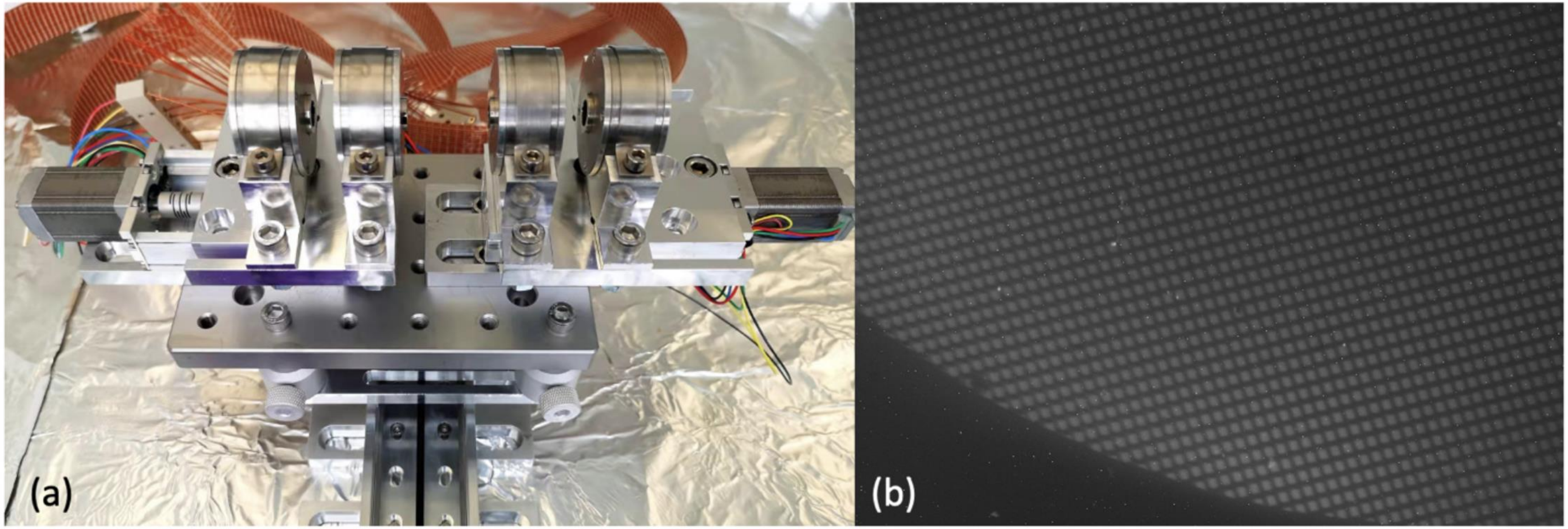


Shadow of the TEM grid (square thick/thin 30um opening/16-10-10um bars) obtained using an improved e-beam imaging system.



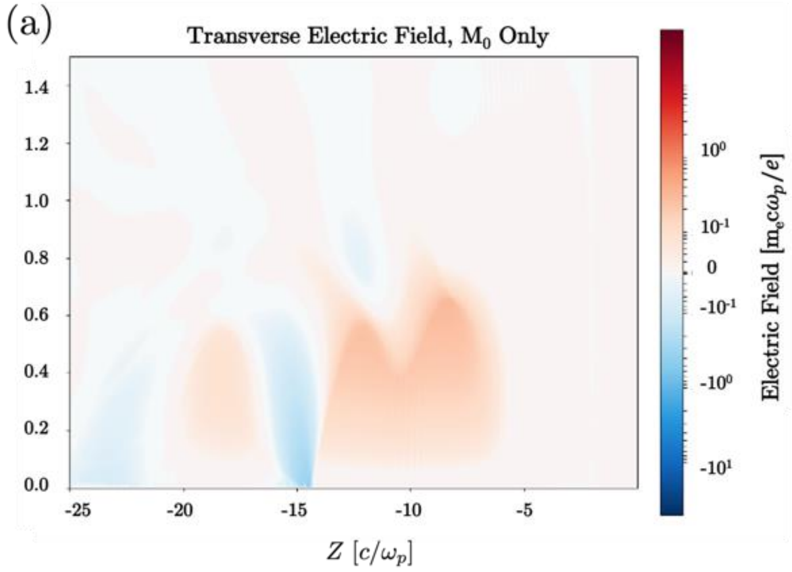
Permanent Quadrupole Diagnostic

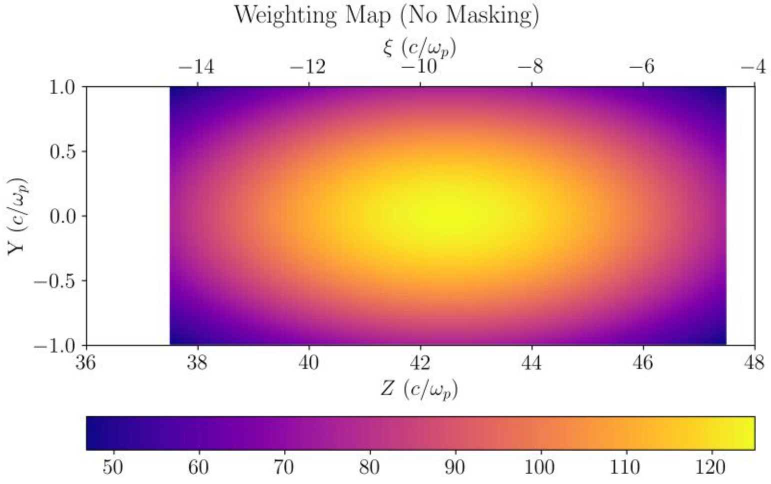
e-beam passing through a grid with (5 μm bar, 7.5 μm spacing)

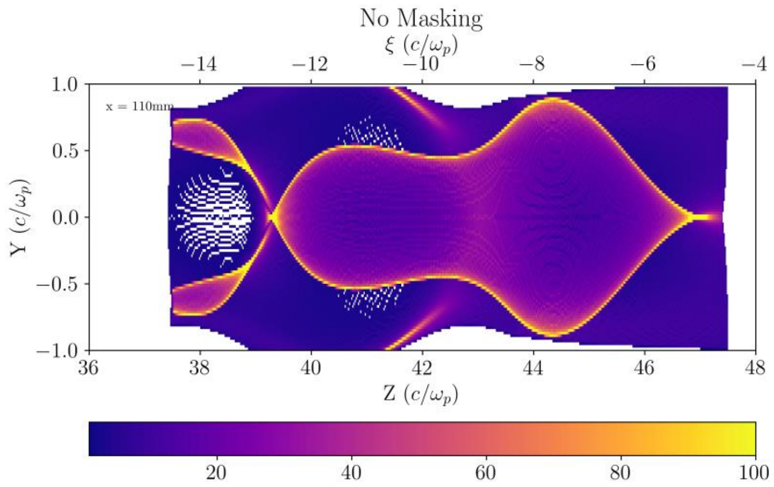


- Permanent Magnet Quadrupoles (PMQs) developed by UCLA have been characterized and used by AE98/99
- This device is available as diagnostic if radiographic information is needed closer to the plasma than the movable BPM can record

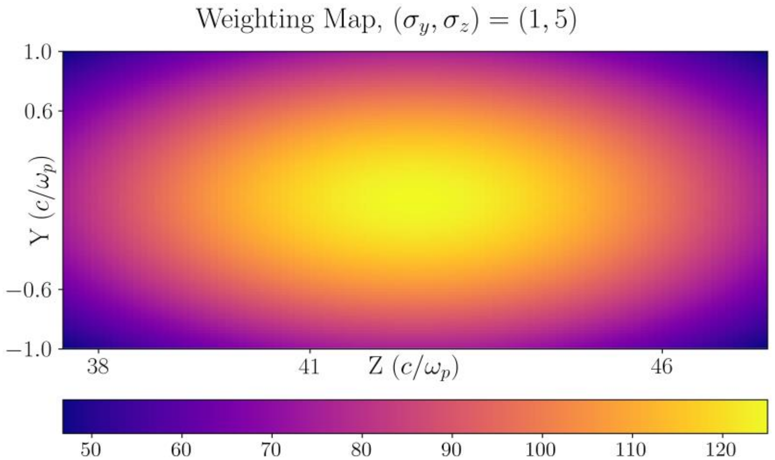
We will Continue Using Beam Probing Simulations



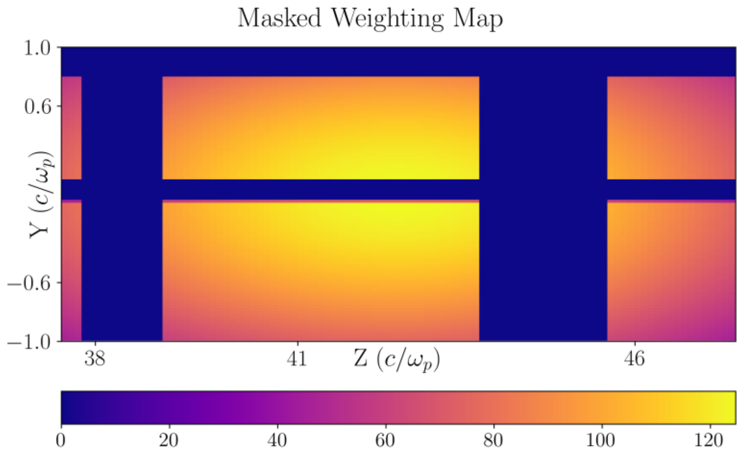




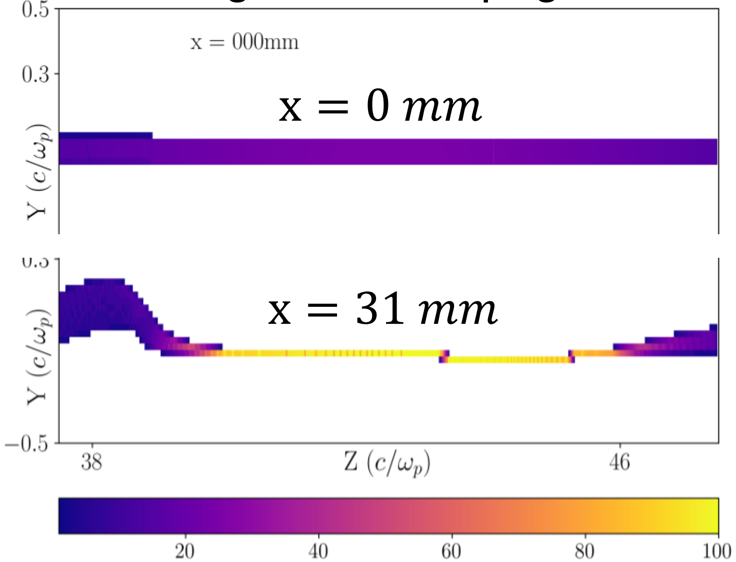
Realistic Beam Shape



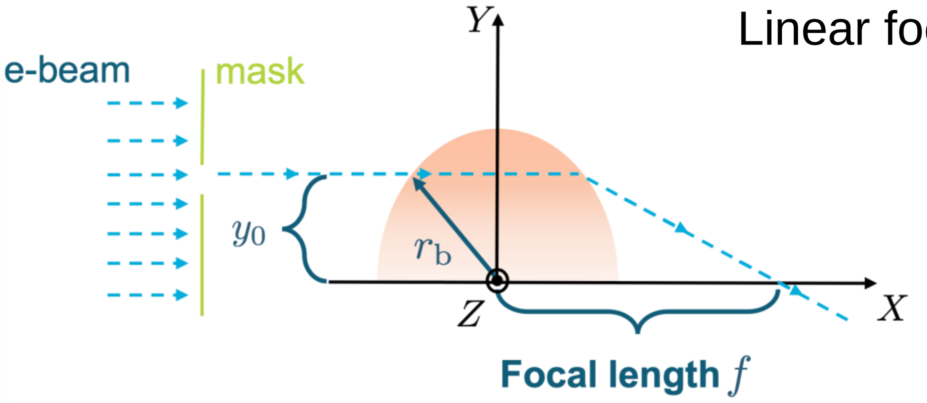
Custom Masks as Postprocessing



Tracking Probe Propagation



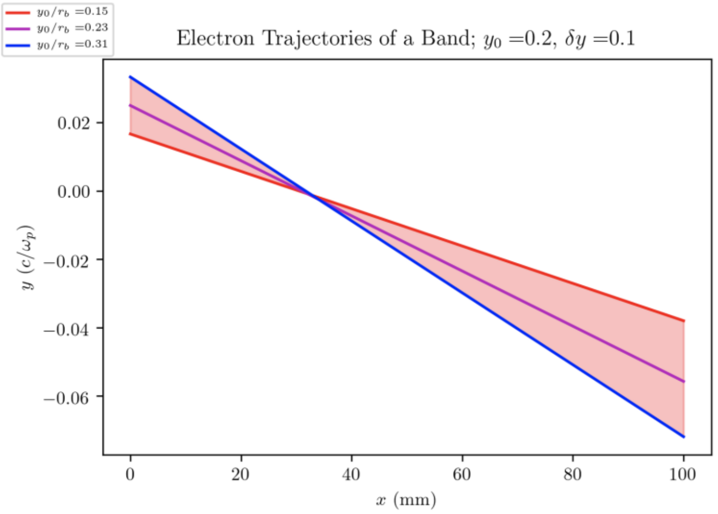
Expansion of Theory Allows Predicting Evolution of “Beamlets”

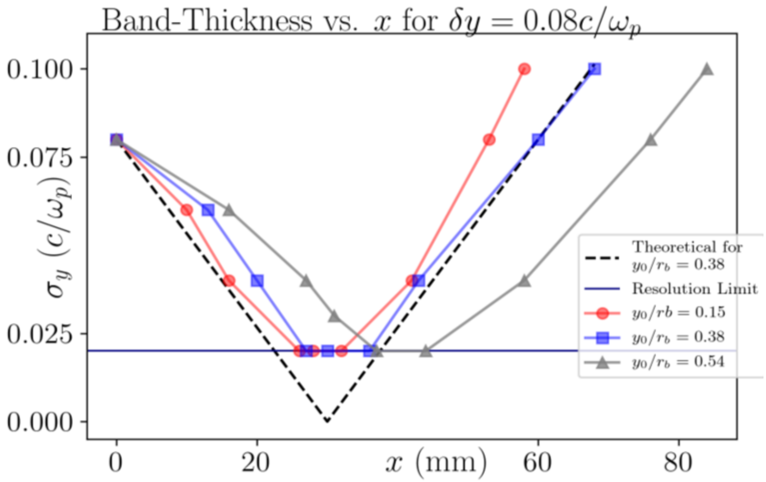


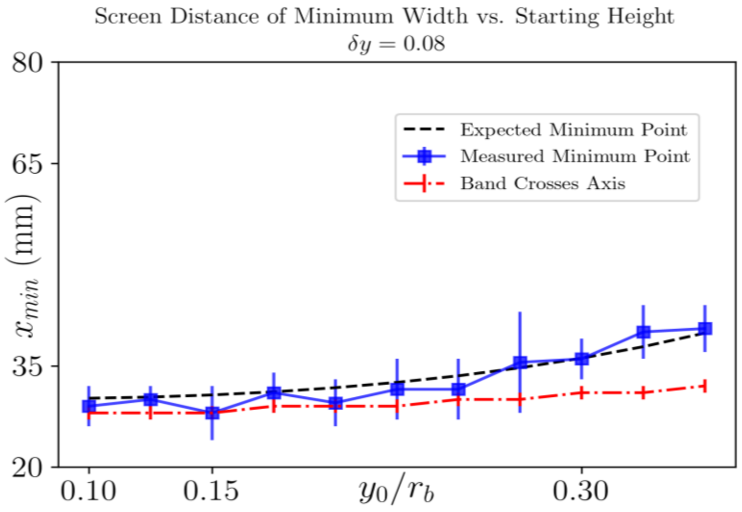
Linear focusing force in a bubble: $F_r = kr$ (wakefield theory suggests $k \approx 0.5$)

$$f \approx \underbrace{\frac{pc}{2F_\perp^{max}}}_{\text{Focal length}} \underbrace{\left(1 - \left(\frac{y_0}{r_b}\right)^2\right)^{-1/2}}_{\text{Depth of field}}, \text{ where } F_\perp^{max} = kr_b$$

If we can measure the focal length, we can characterize the field inside the bubble.

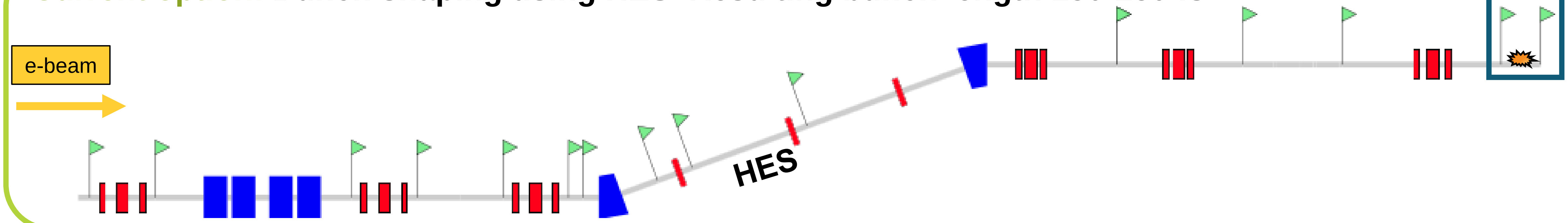


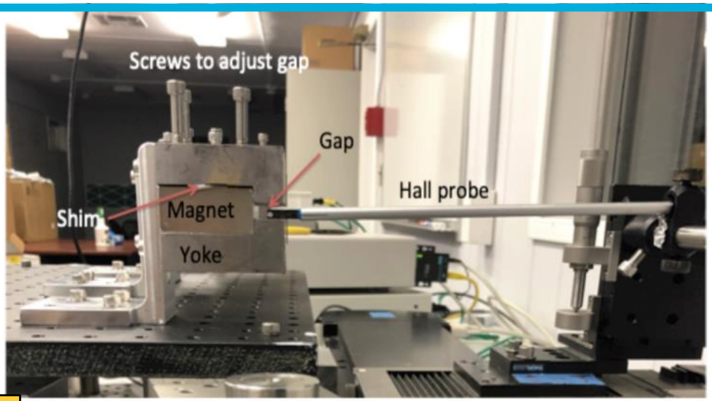




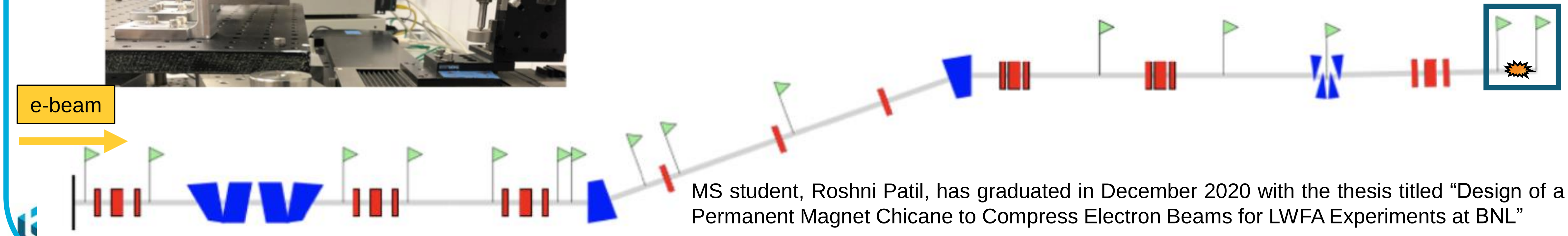
Other Work: Implementation of e-beam Compression Scheme

Current option: **Bunch shaping using HES. Resulting bunch length 150-250 fs.**





Future option: **Bunch shaping using chicane**



MS student, Roshni Patil, has graduated in December 2020 with the thesis titled "Design of a Permanent Magnet Chicane to Compress Electron Beams for LWFA Experiments at BNL"

Summary of Major Goals:

- Use the movable BPM to demonstrate operation of CO_2 driven LWFA in blowout regime for the first time.
- Examine the fields in the transition regime of SM-LWFA to blowout regime.
- Map out the nonlinear fields of LWFA in various interaction regimes parameterized by plasma density, location of the focus spot (the z scan), and distance behind the laser (laser e-beam delay).
- Identify the physics of electron injection. Since electron injection occurs near axis, we will use masks to focus on fields near the axis
- Correlate findings with electron beam spectrometer and laser diagnostics
- Compare the properties of the fields (in particular, the linearity of focusing fields) with those expected from simulations and theory.

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 (~55 MeV)*
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	*Max possible at max 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*	*100 fs (minimum)*
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.*	*2 mm (horizontal)* *0.5 mm (vertical)*
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	*1*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	*1.5*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	*Single bunch*

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.*	*2-5*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2*
Brookhaven National Laboratory	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	*5*
	M^2	[illegible]	[illegible]		[illegible]

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*	*N/A*
FWHM Bandwidth	nm	20	13		*N/A*
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.*	*N/A*
Chirped FWHM Pulse Width	ps	≥50	≥50		*N/A*
Chirped Energy	mJ	10	200		*N/A*
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.*	*N/A*
Energy to Experiments	mJ	>4.9	>80		*N/A*
Power to Experiments	GW	>98	>1067		*N/A*

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

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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.: **bunch shortening using HES**

CO_2 Laser

- Please note any specialty laser configurations required here: N/A

Ti:Sapphire and Nd:YAG Lasers

- Please note any specialty non-CO_2 laser configurations required here: N/A

Hazards & Special Installation Requirements

- Large installation (chamber, insertion device, etc.): N
- Cryogens: N
- Introducing new magnetic elements: Y
- Introducing new materials into the beam path: Y
- Any other foreseeable beam line modifications: N

Experimental Time Request

CY2024 Time Request

Capability	Setup Hours	Running Hours
Electron Beam	20	100*
NIR Laser	-	-
LWIR Laser	40	100*

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

Capability	Setup Hours	Running Hours
Electron Beam	60	300*
NIR Laser	-	-
LWIR Laser	120	300*

*Note: Experiment needs LWIR and Electron Beam Simultaneously.
Therefore, the running hours are meant to be simultaneous, not additional.