External Injection of an Electron Beam in LWIR-Driven LWFA

Navid Vafaei-Najafabadi
(on Behalf of AE 93/95)

Plasma Acceleration Group

Center for Accelerator Science and Education

Stony Brook University

Synthesis

ATF's short pulse mid-IR laser makes it a unique facility for LWFA research

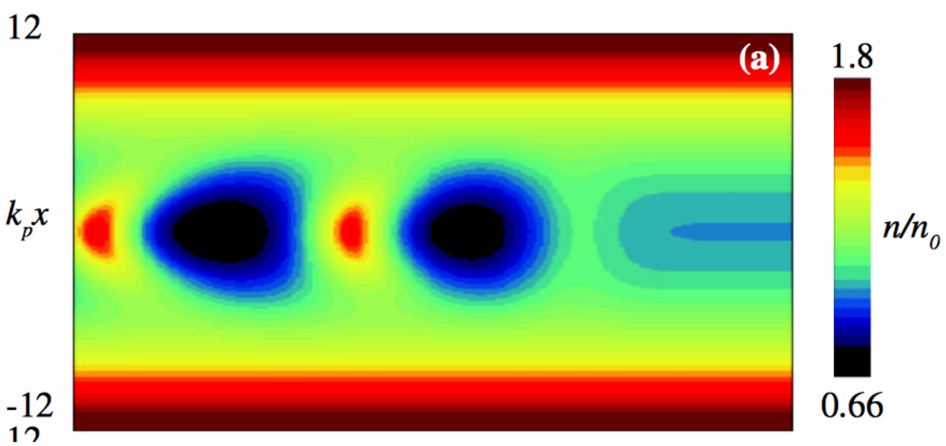
Collection of additional capabilities create opportunities for unique plasma diagnostics

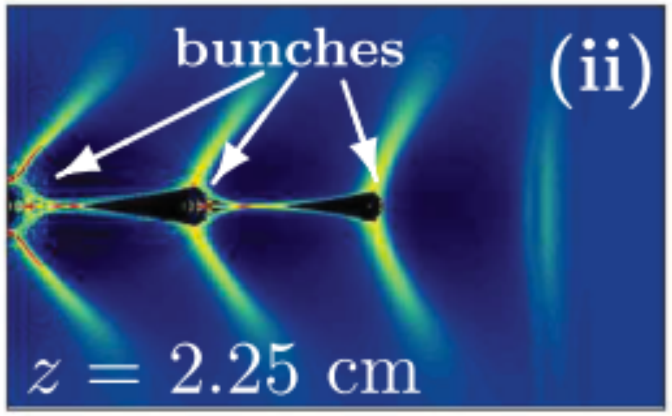
Primary LWFA experiments of interest are external injection, e-beam probing of the evolution of plasma structures, two color ionization injection, and LWFA to PWFA scheme

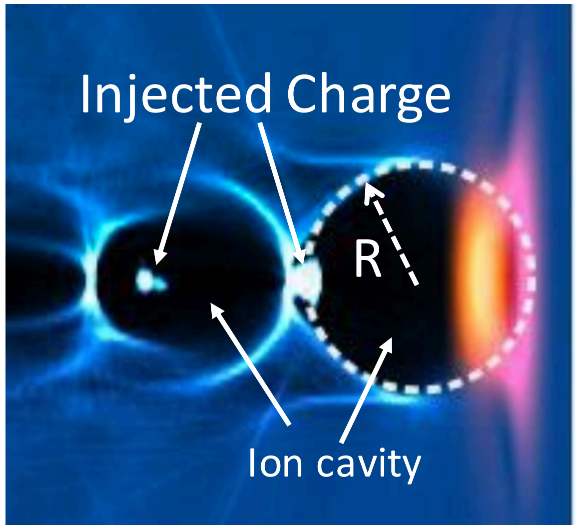
As part of two experiments (AE93/95), we have started to explore the TW-class CO_2 laser and plasma interaction

Stony Brook University

Laser Driven Plasma Wakes







$a_0 > 1$: Nonlinear Regime

$a_0 > 2$: Blowout Regime

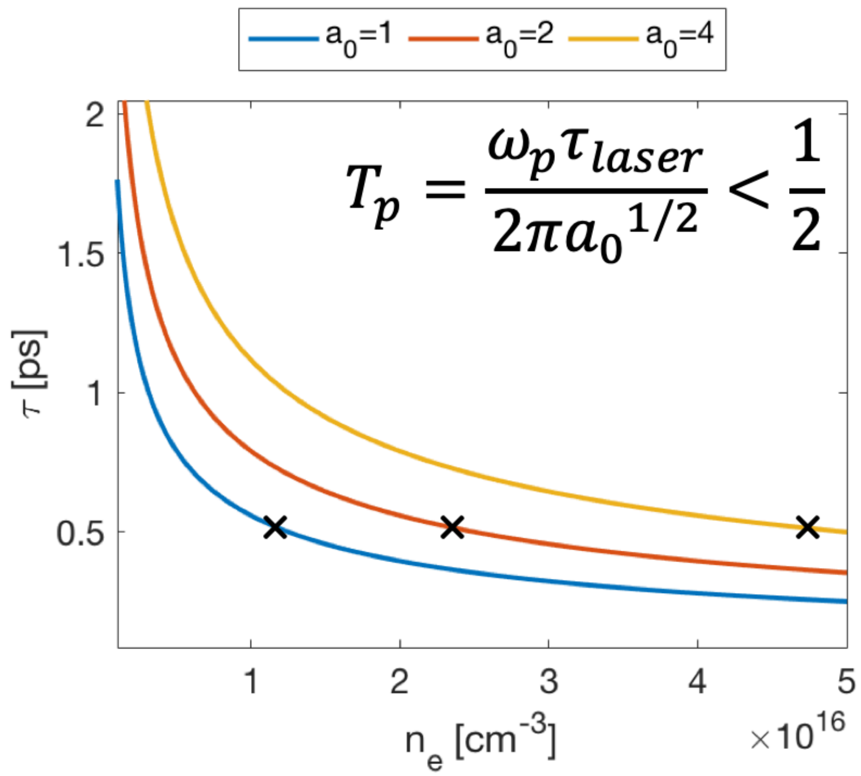
$a_0 > 4$: Bubble Regime (Spherical Blowout)

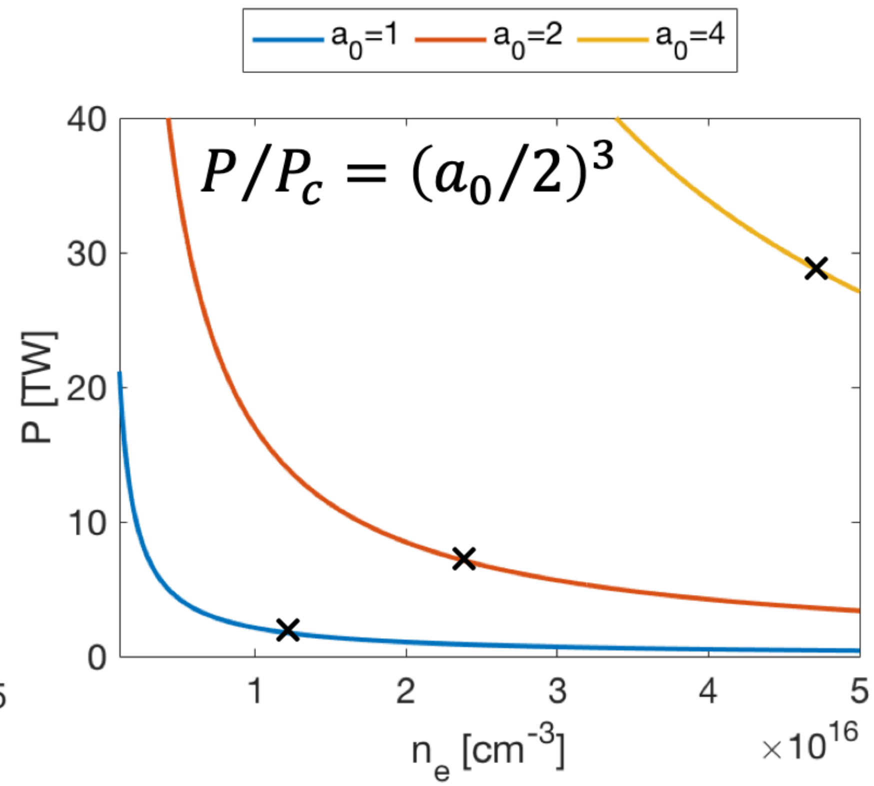
Vector Potential $a_0 = \dfrac{eA_{laser}}{mc^2} = 8.6 \times 10^{-10}\sqrt{I[Wcm^{-2}](\lambda[\mu m])^2}$

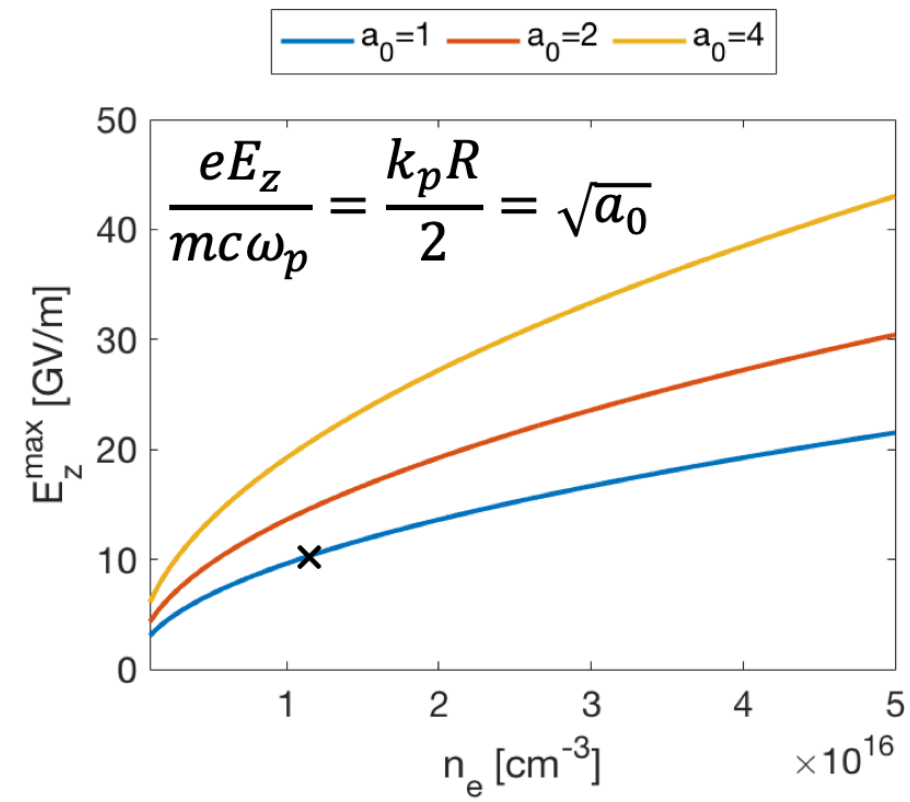
High accelerating field and linear focusing forces in the bubble regime are very advantageous for electron acceleration

C. B. Schroeder PRSTAB **13** 101301 (2010)
W. Leemans, et al. PRL **113** 245002 (2014)
W. Lu, et al., PRSTAB **10** 61301(2007)

Matched Conditions



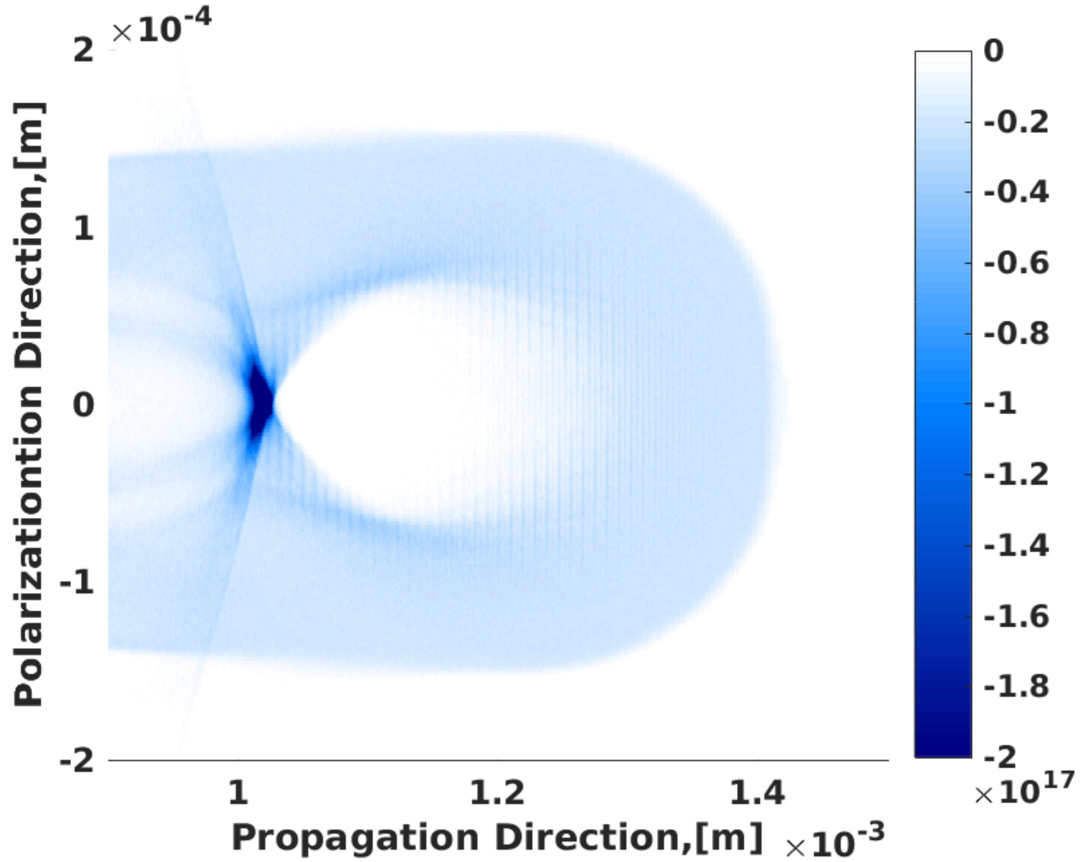


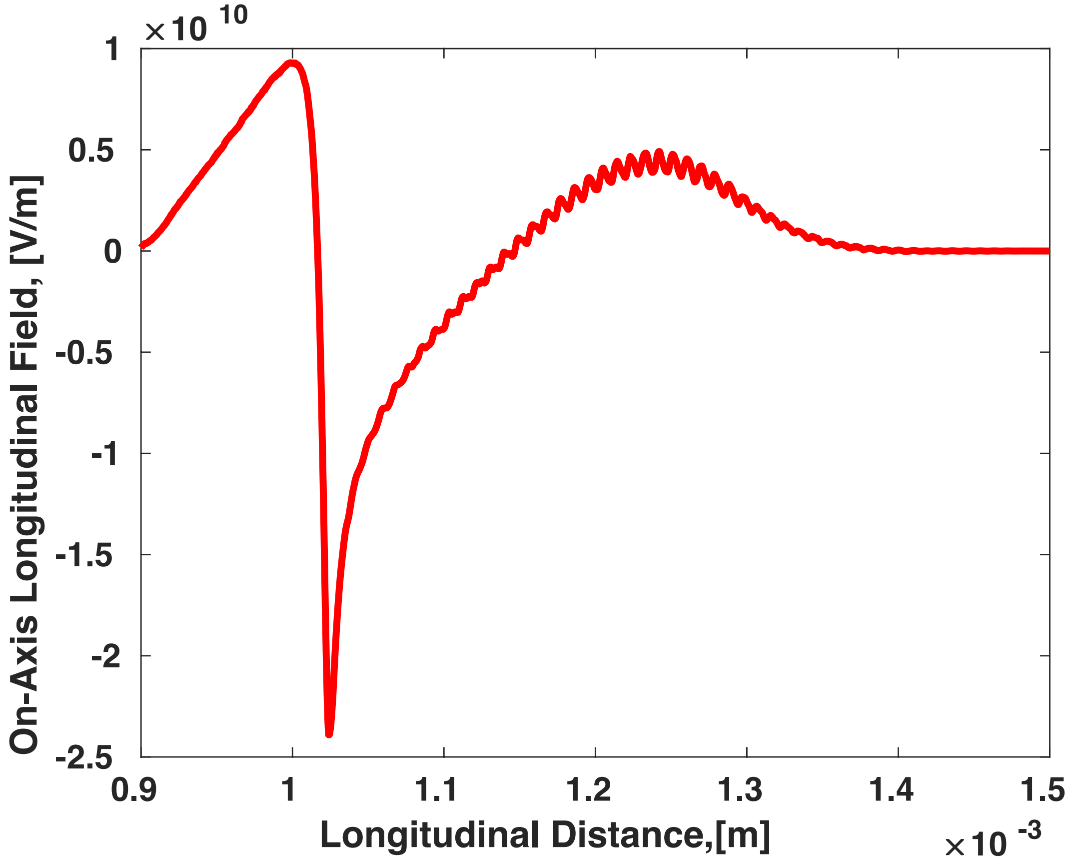


a_0	Wakefield Characterization	P (TW)	n_e (cm^{-3})	E_z^{max}(GV/m)
1	Nonlinear Regime	2	1.2e16	11
2	Blowout Regime	7	2.5e16	21
4	Bubble Regime	27	5.0e16	43

In a matched scenario, 27 TW is needed to reach $a_0 \sim 4$, but bubble regime can be reached by a 20 TW, 0.5 ps pulse in an *unmatched* case.

Blowout regime reached with $a_0 \sim 4$



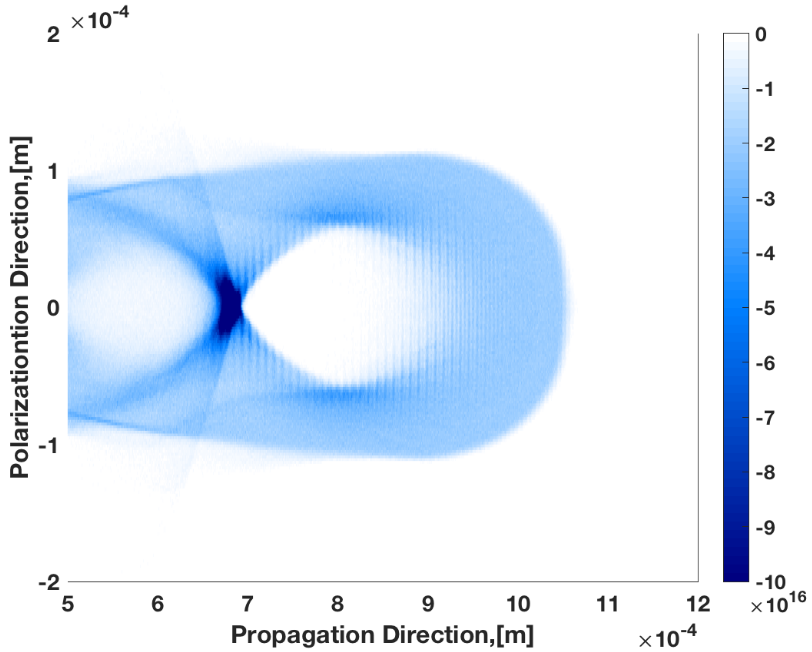


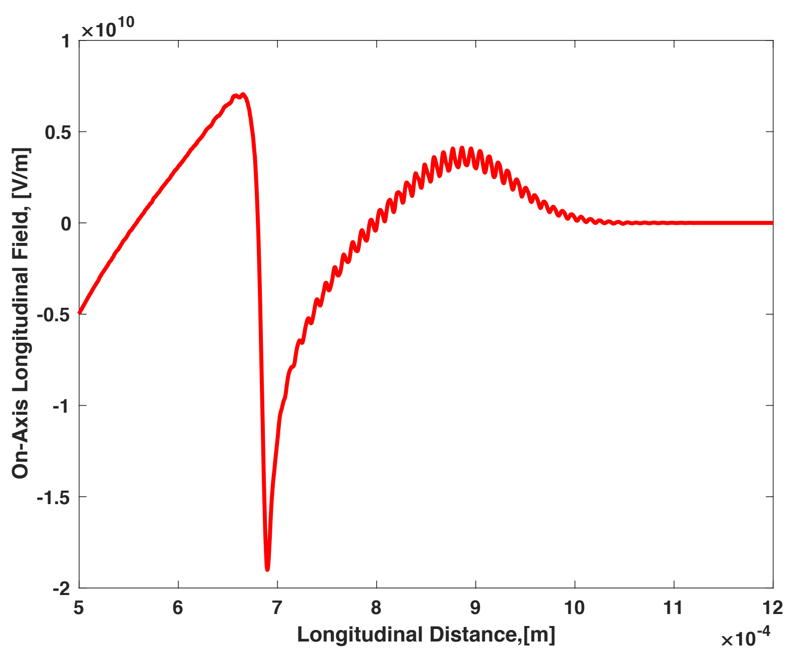
Simulation Parameters	
Power	20 TW
Pulse Length	0.5 ps
Spot size	74 μm
Plasma Density	$2.6 \times 10^{16}\ cm^{-3}$

Simulation Results	
a_0	3.8
R_b	80 μm
E_{max}	24 GV/m

Simulation performed with the code SPACE

Reducing Power or Pulse Length



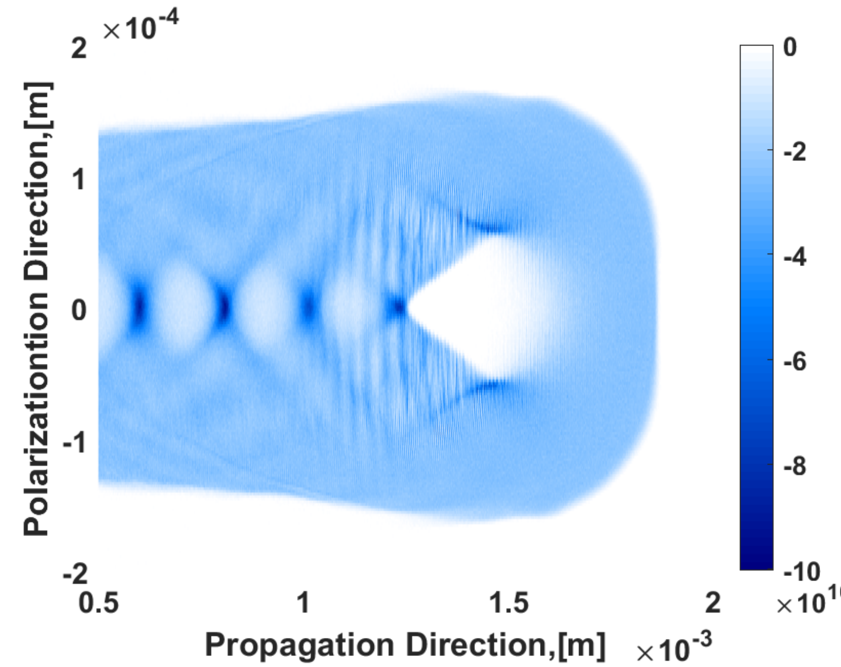


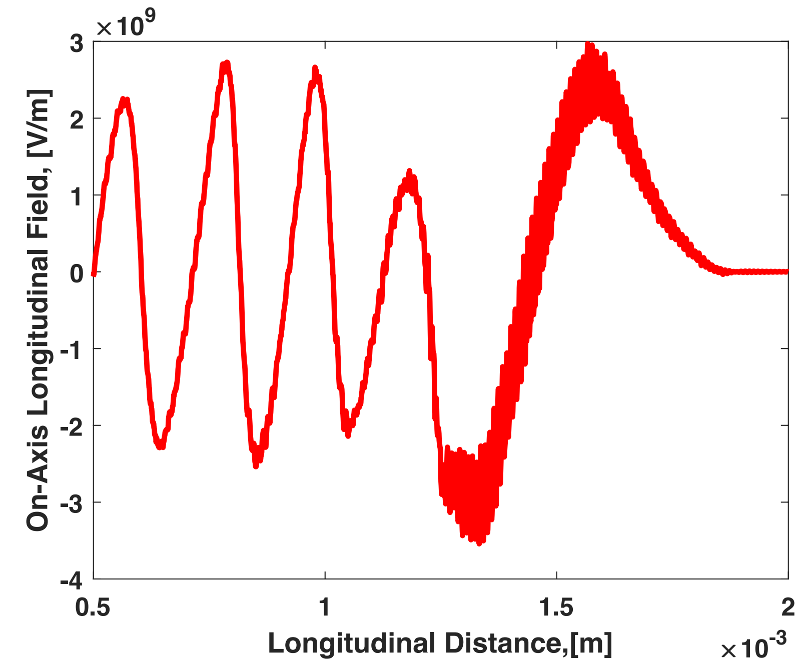
10 TW

$\tau \sim 0.5\ ps$

$a_0 \approx 4$

$w0 = 50\ \mu m$





20 TW

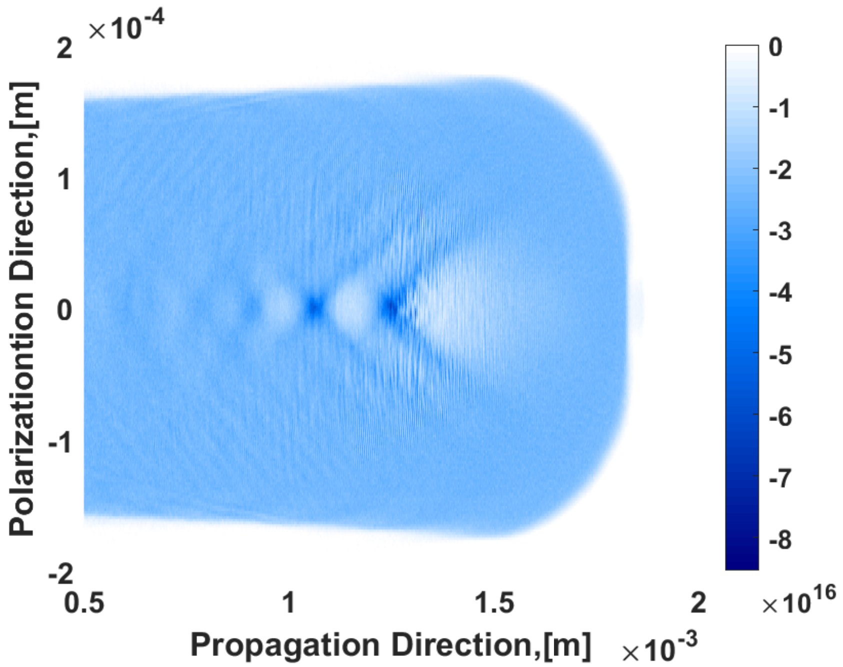
$\tau \sim 1\ ps$

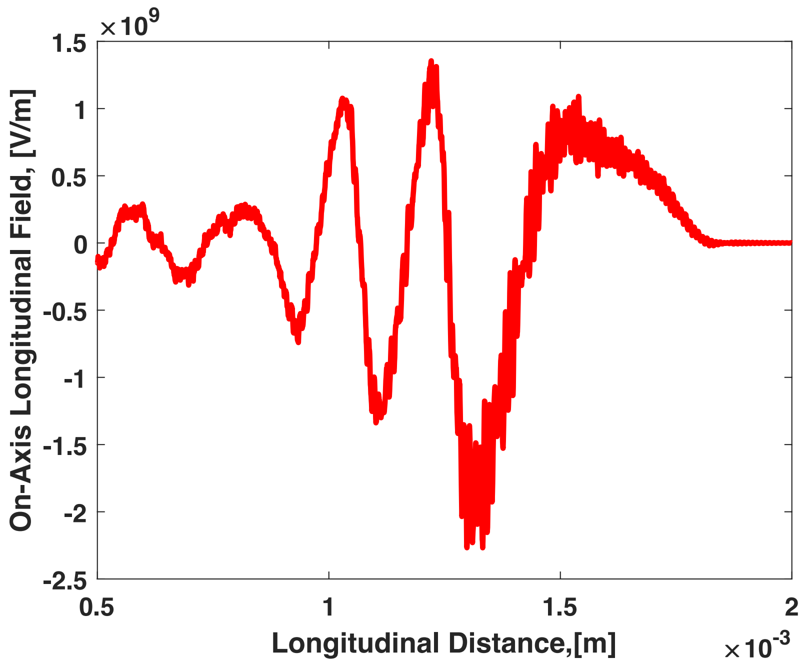
$a_0 = 3.8$

$w_0 = 74\ \mu m$

Stony Brook University

Reducing a_0 to 2

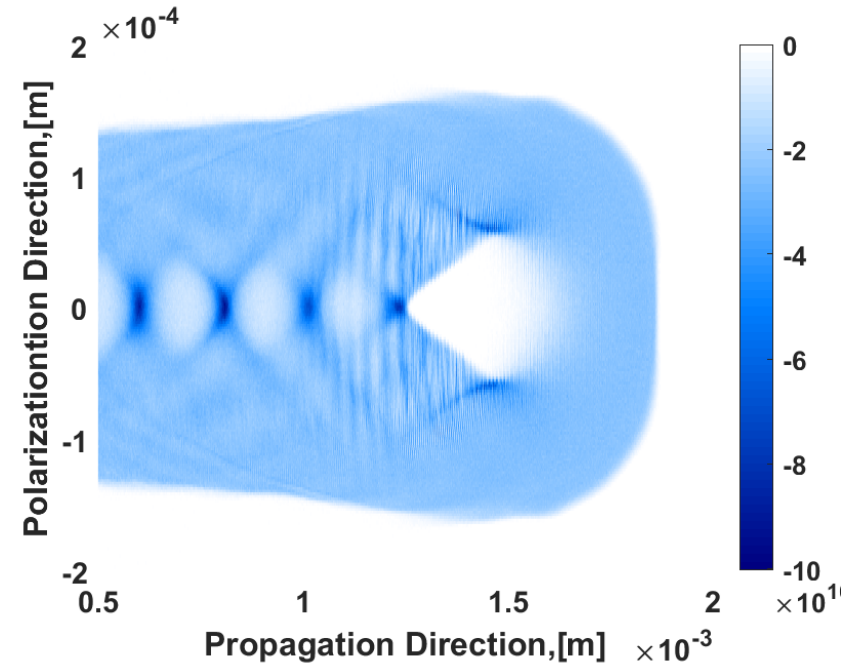


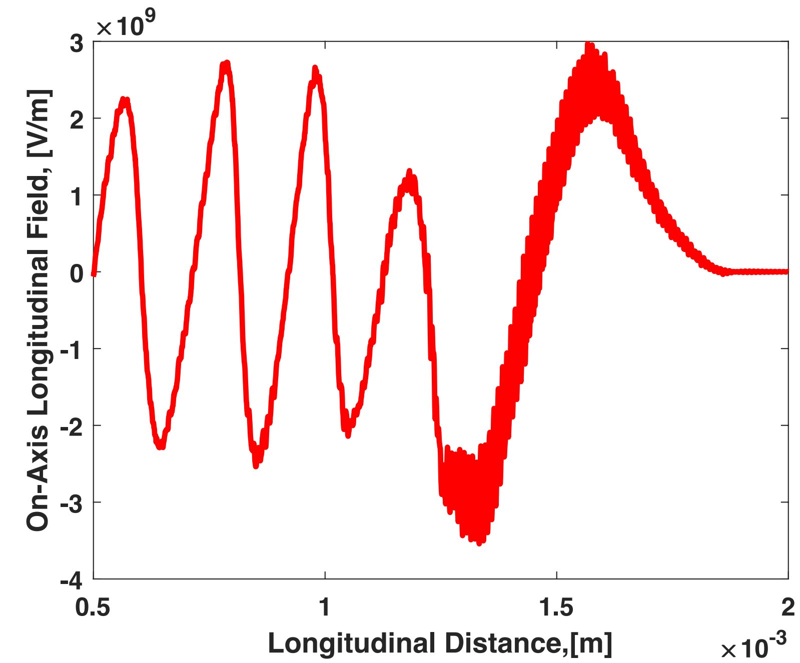


10 TW

$a_0 = 2.01$

$w_0 = 99\ \mu m$





20 TW

$a_0 = 3.8$

$w_0 = 74\ \mu m$

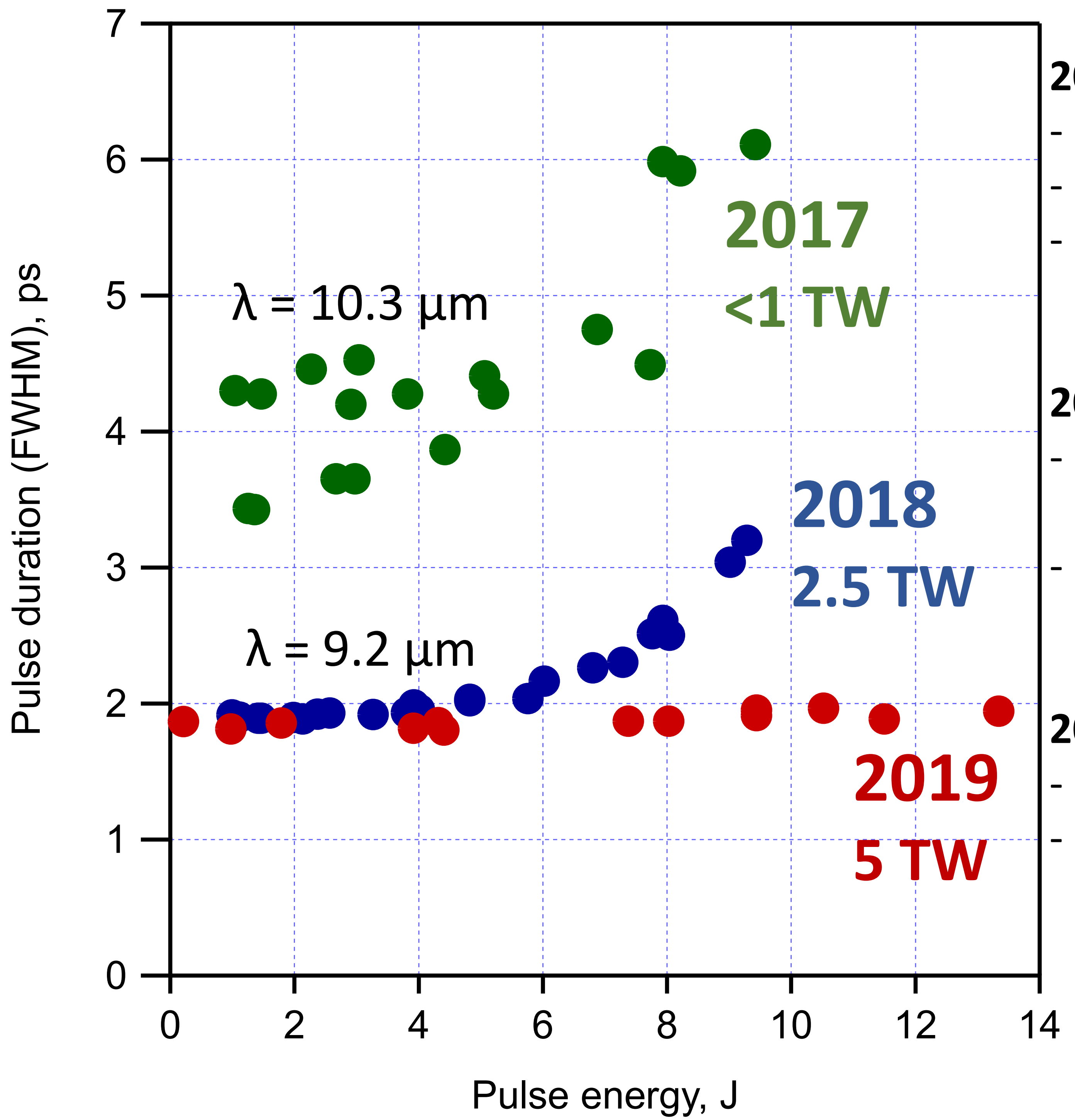
ATF's roadmap is consistent with this vision

Today	2020	2021	2022
2 TW	5 TW	10 TW	20 TW
2 ps	2ps	1 ps	0.5 ps

Both power and small pulse lengths are needed for reaching the blowout regime, as the ponderomotive force is proportional to the *gradient* of intensity

Towards Sub-ps CO_2 Pulses at ATF

Recent CPA CO_2 laser development



2017

- mixed-isotope regen
- 66 % of energy in 1st pulse
- compressor efficiency 50 %

2018

- mixed-isotope regen <u>and</u> final amplifier
- 87 % of energy in 1st pulse

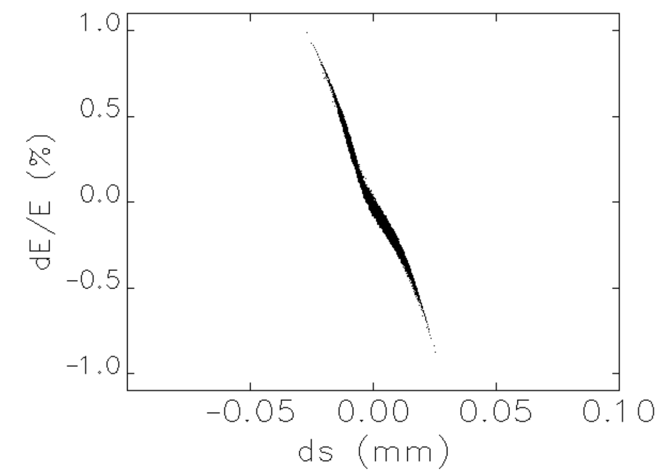
2019

- 2× chirp (denser gratings)
- compressor efficiency 70 %

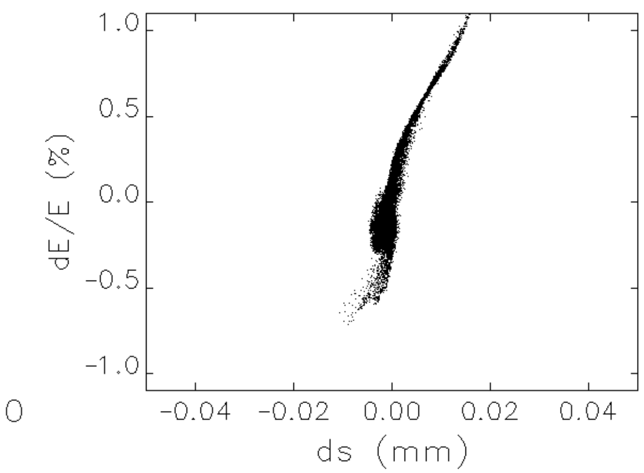
Stony Brook University

Addition of a zig-zag compression will produce <20 fs e-beam for probing and external injection

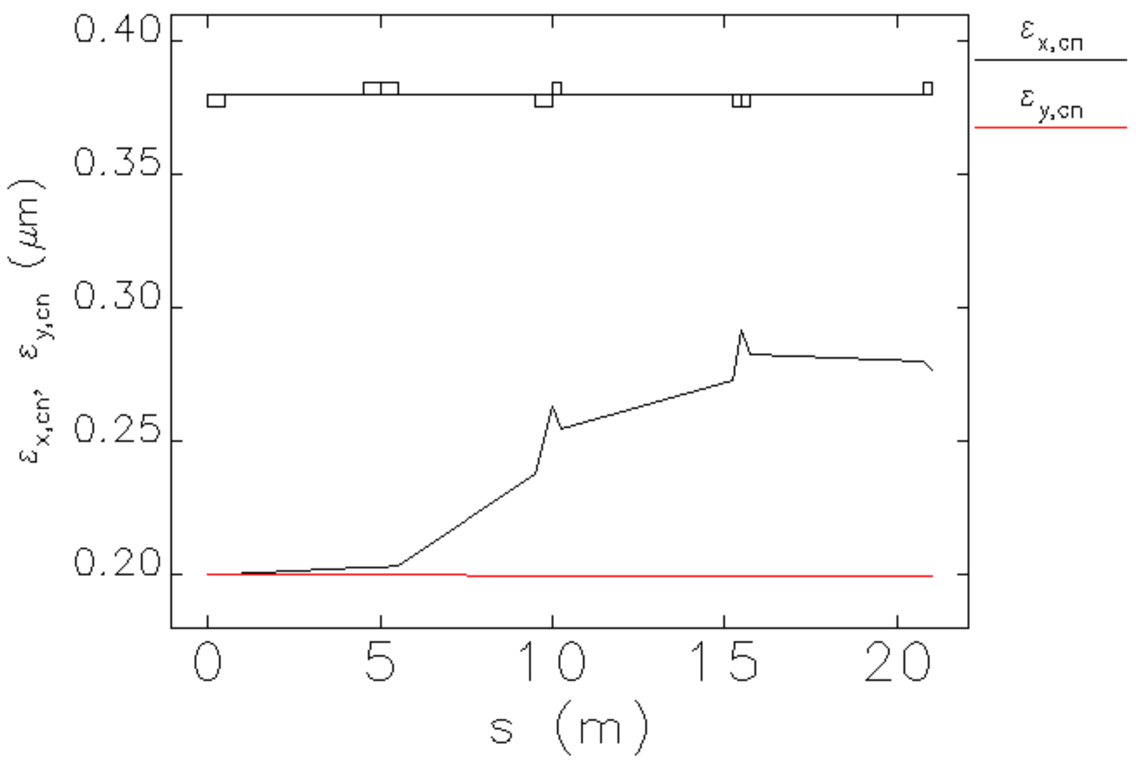
Energy, MeV	70
Rms energy spread	0.1%
Bunch length, mm	0.06
Chirp, m-1	20
Bunch length, rms, fsec	12



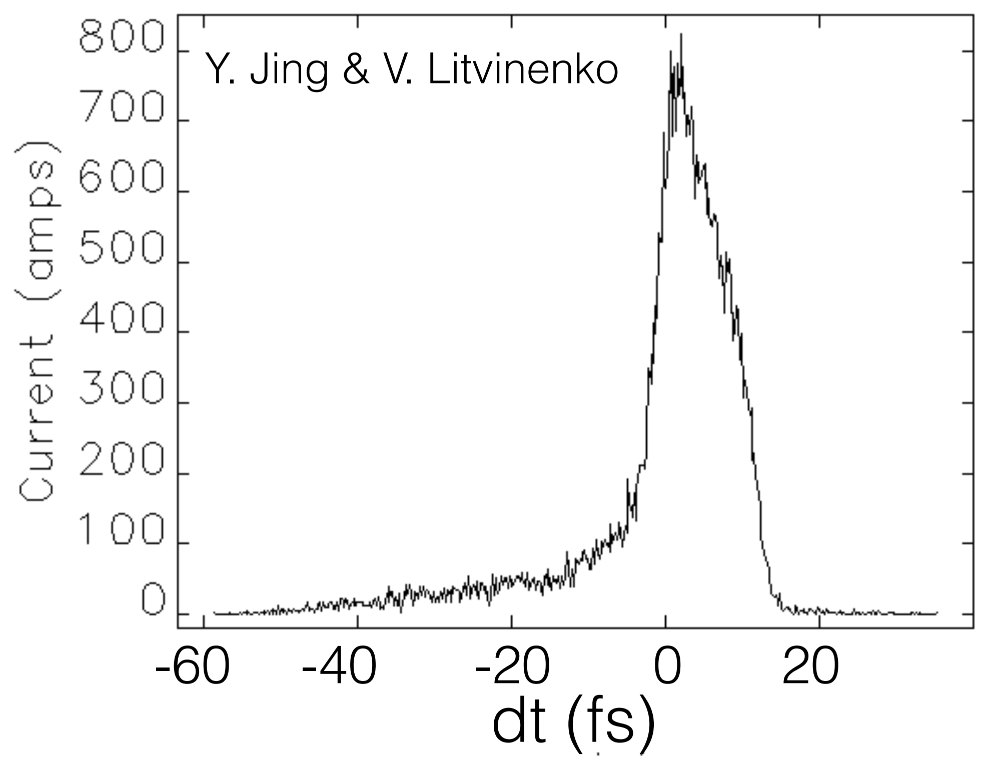
Before 2nd Chicane



After 2nd Chicane



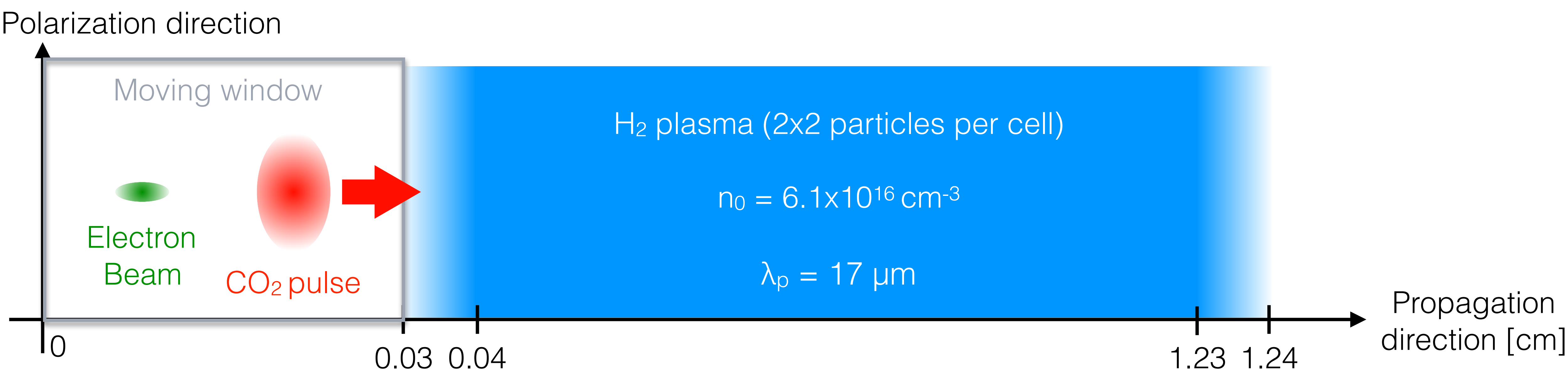
Normalized Emittance along Beamline



Current Profile

The compressed electron beam will be a unique source for probing as well as external injection in LWFA experiments

ATF e-beam can be used to characterize external injection into an LWFA



	Duration	Power	λ_0	Spot size	Energy	Intensity	a_0	Rayleigh length	Critical power	Critical Density	Depletion length	Dephasing length
Laser	**0.2 ps**	**20 TW**	9 μm	**80 *μm***	4.3 J	3.2×10^{18} W/cm^{-2}	14	0.014 cm	0.06 TW	1.4×10^{19} cm^{-3}	1.4 cm	1.2 cm

	Charge	FWHM length	σ_z	σ_r	n_p/n_0	Energy	Emittance	Particles per cell
e^- beam	**0.16 nC**	**30 fs**	3.8 μm	11 μm	2.3	60 MeV	7.5 μm	2x2

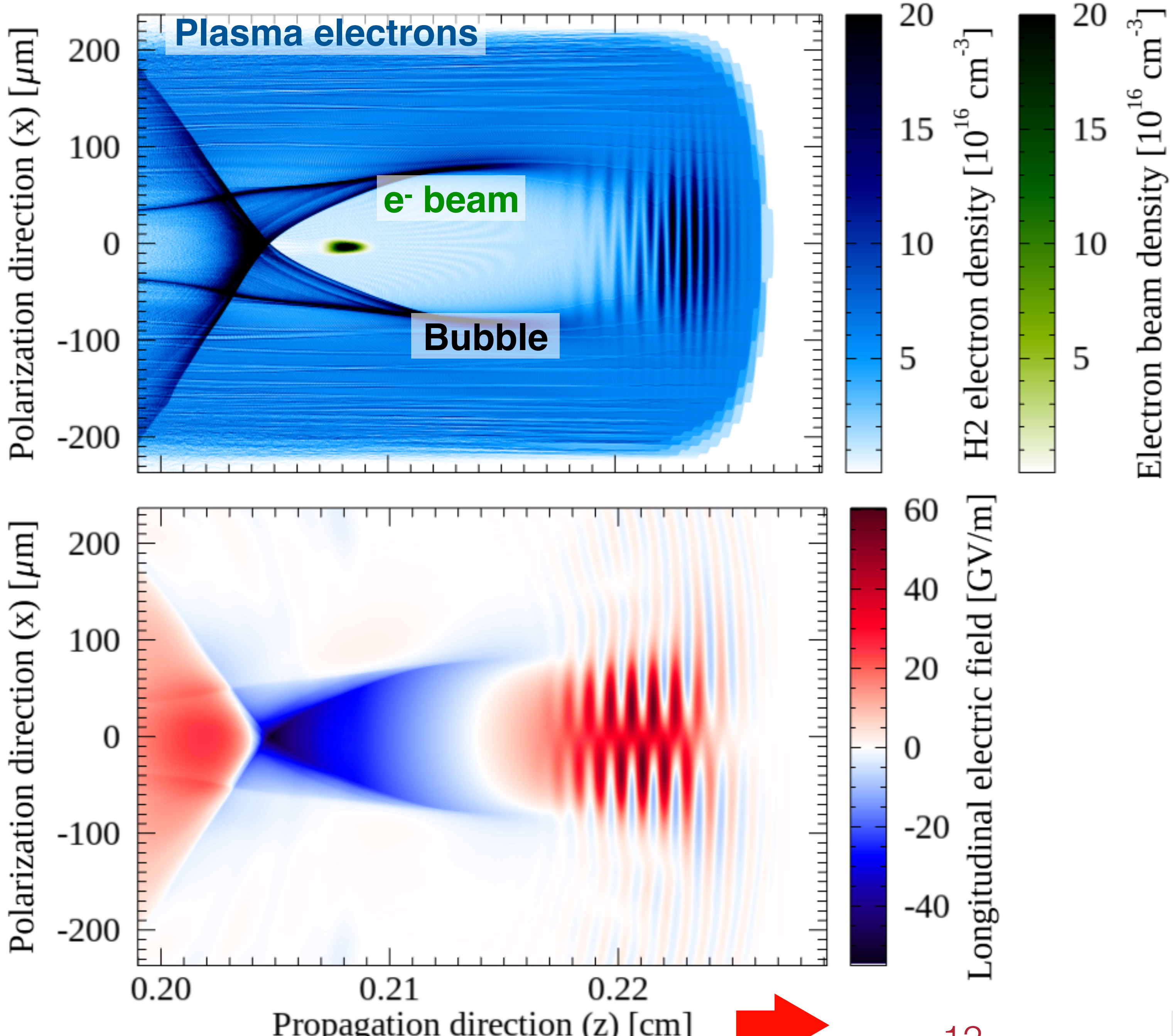
	Simulation box - Longitudinal			Simulation box - Transversal			
	Size	**Cells per λ_0**	**Cells per c/ω_p**	**Size**	**Cells p. spot size**	**Cells per c/ω_p**	**Ionization**
Simulation box	303 μm	120	288	475 μm	80	296	Active - ADK

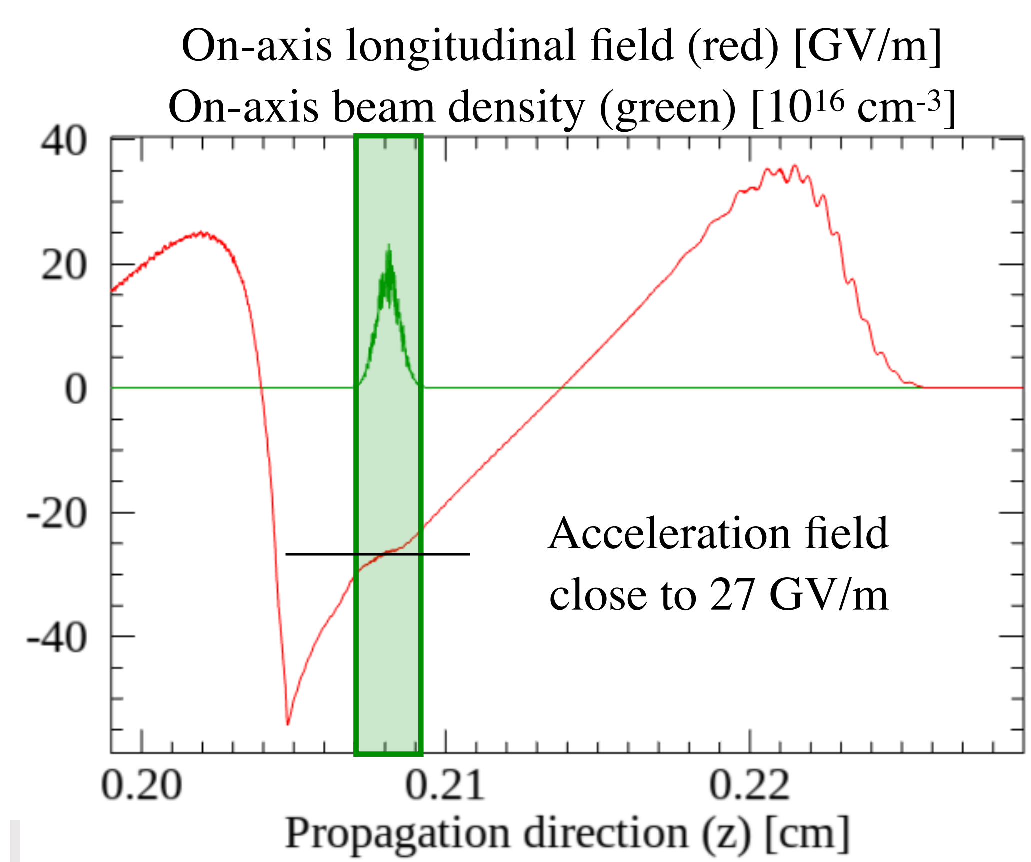
Externally injected beam is accelerated in a ≈170μm bubble driven by CO_2 laser

Compressed to ≈200 fs, CO_2 laser can drive plasma wakes as long as 170μm

The external injection of ATF's e⁻ beam into accelerating phase with ≈25 GeV/m can be used to model multi-stage LWFA injection and acceleration

Higher-energy ATF beam will enable external injection experiment in the "dephasing" regime





Near-IR capabilities will create new tools for diagnostics and injection experiments

New diagnostic capabilities will be enabled by the addition of expanded near-IR capabilities

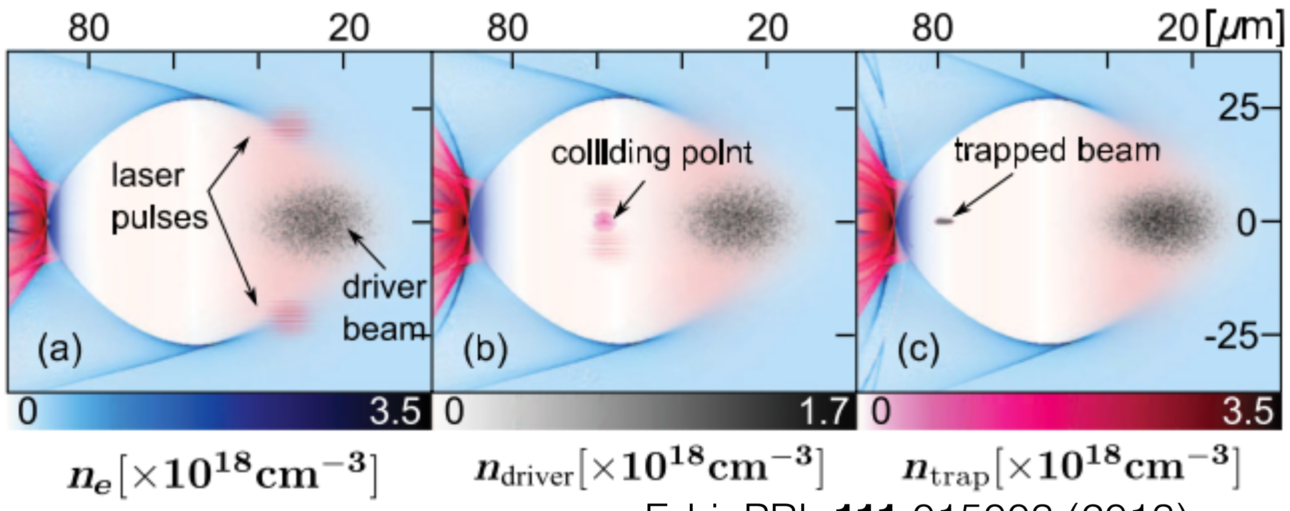
Longitudinal Probe Diagnostics

- **B** of electron probe using Faraday rotation
- Probe sidebands vs Δt with beam loading
- Probe sidebands vs n_e down to 10^{17} cm^{-3}

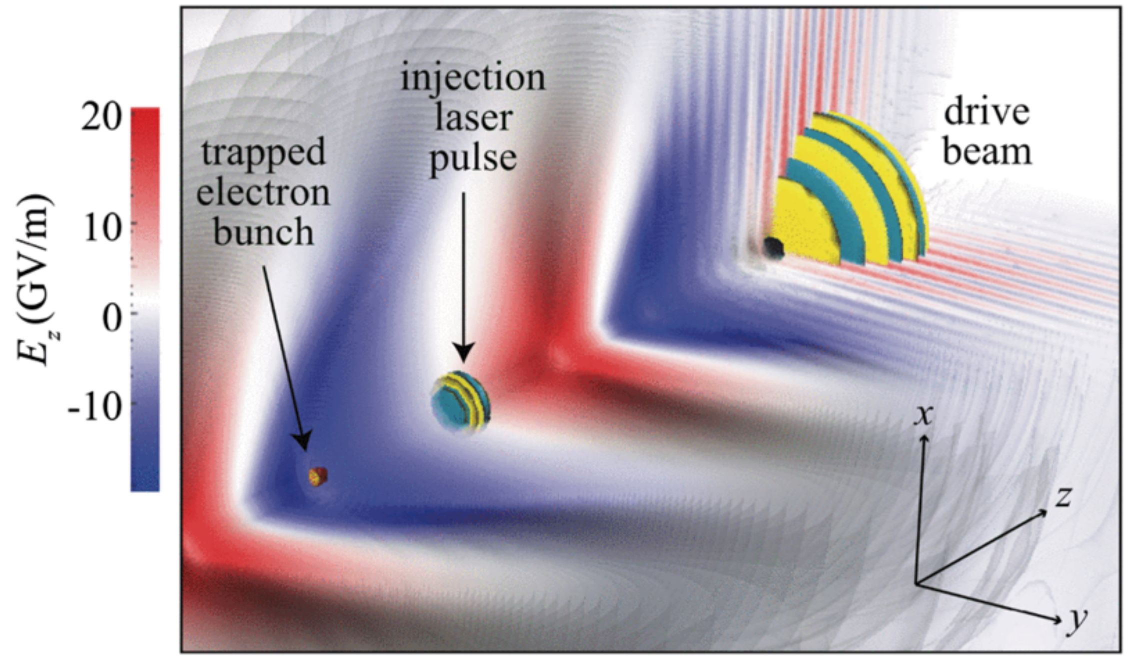
Transverse CTS probe

- $\Delta\omega = \pm\,\omega_p$ and $\Delta k = \pm\,k_p$
- Complements e-beam probe
- One-shot image of wake propagation dynamics

"Two-color" ionization injection enabled by the new near-IR lasers will aim at generating high-quality beams

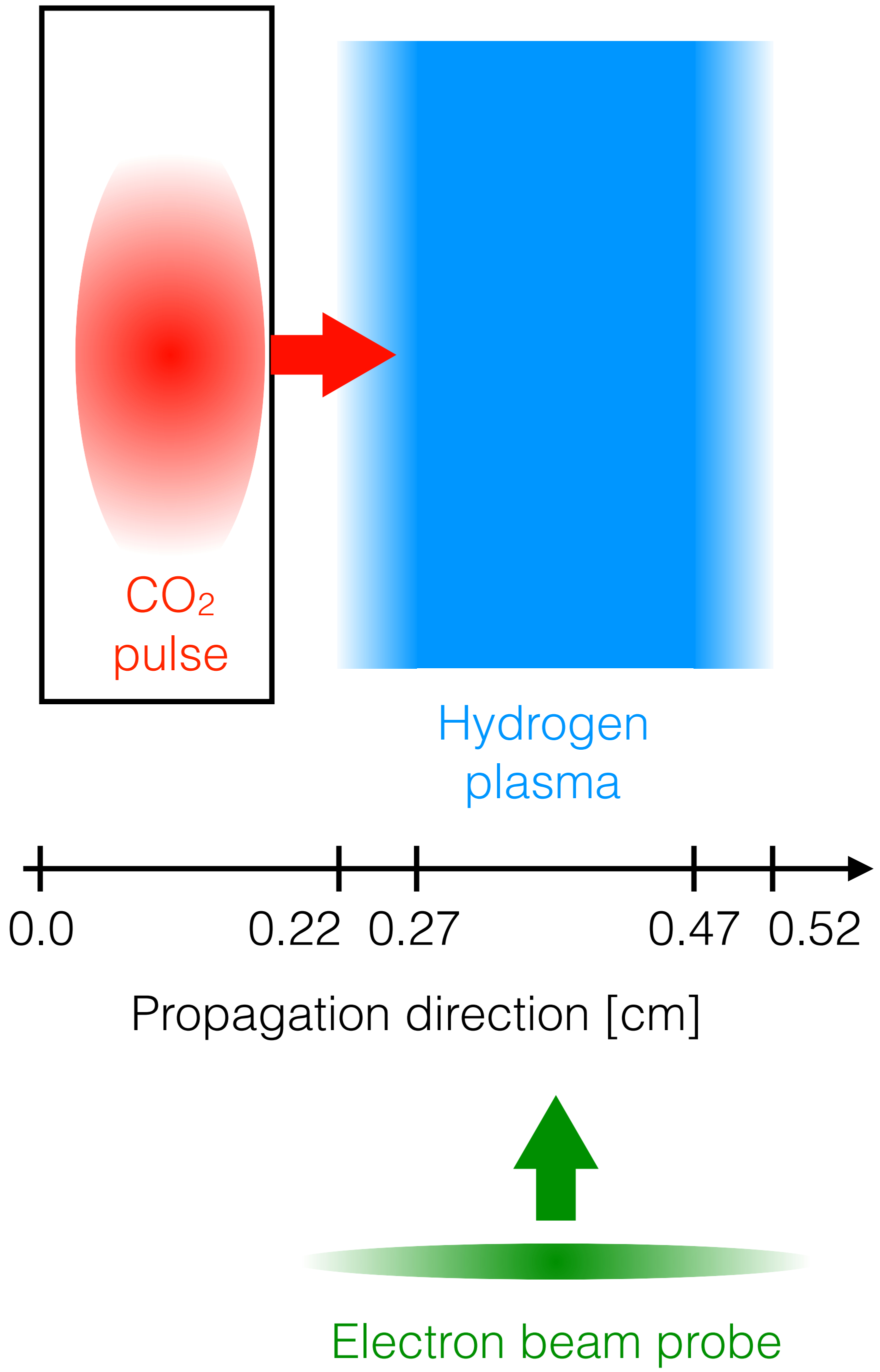


F. Li, PRL **111** 015003 (2013)



C. B. Schroeder, PRAB **17** 101301 (2014)

ATF e^- beam can be used as probe



	W_0	λ_0	τ (FWHM)	En	Z_R	a_0
CO2	20 µm	9.2 µm	**2ps**	**4J**	0,012cm	**4.3**

	n_{0b}	Q	σ_z	σ_x/σ_y	En	ppc
e^- beam	$4.4 \times 10^{13} cm^{-3}$	1nC	30fs	1mm	60 MeV	2x2

	n_0 (ions/e-s)	Skin depth c/ω_p	Particles per cell
H_2 plasma	**$7.5 \times 10^{17} cm^{-3}$**	6.14 µm	2 x 2

Time step: dt = 0.03

Simulation done in 2D geometry

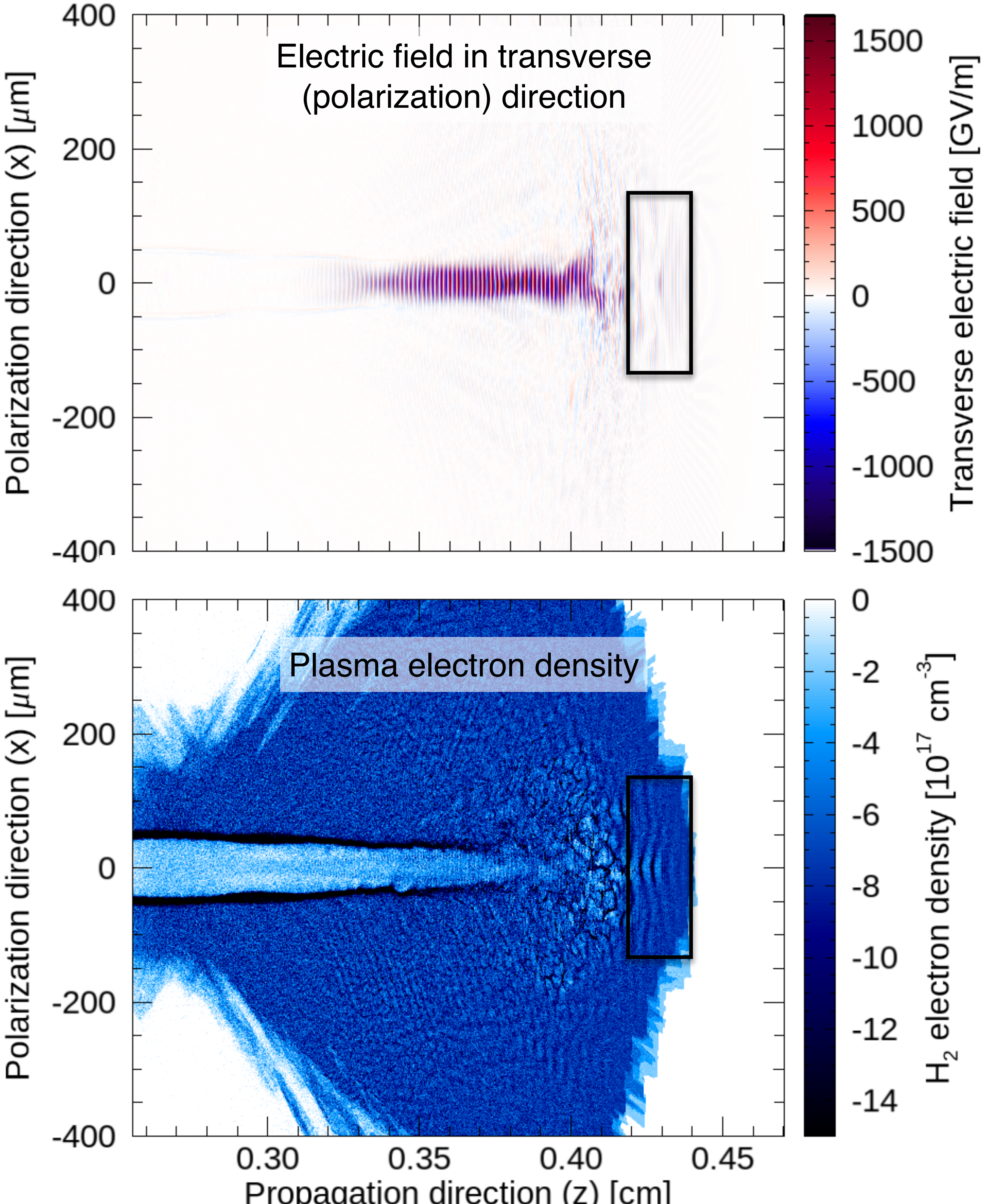
With ADK model of ionization with mobile ions

Moving window (0.21cm long / 0.36cm wide)

Longitudinally:
9400 cells
(60 per λ_0)

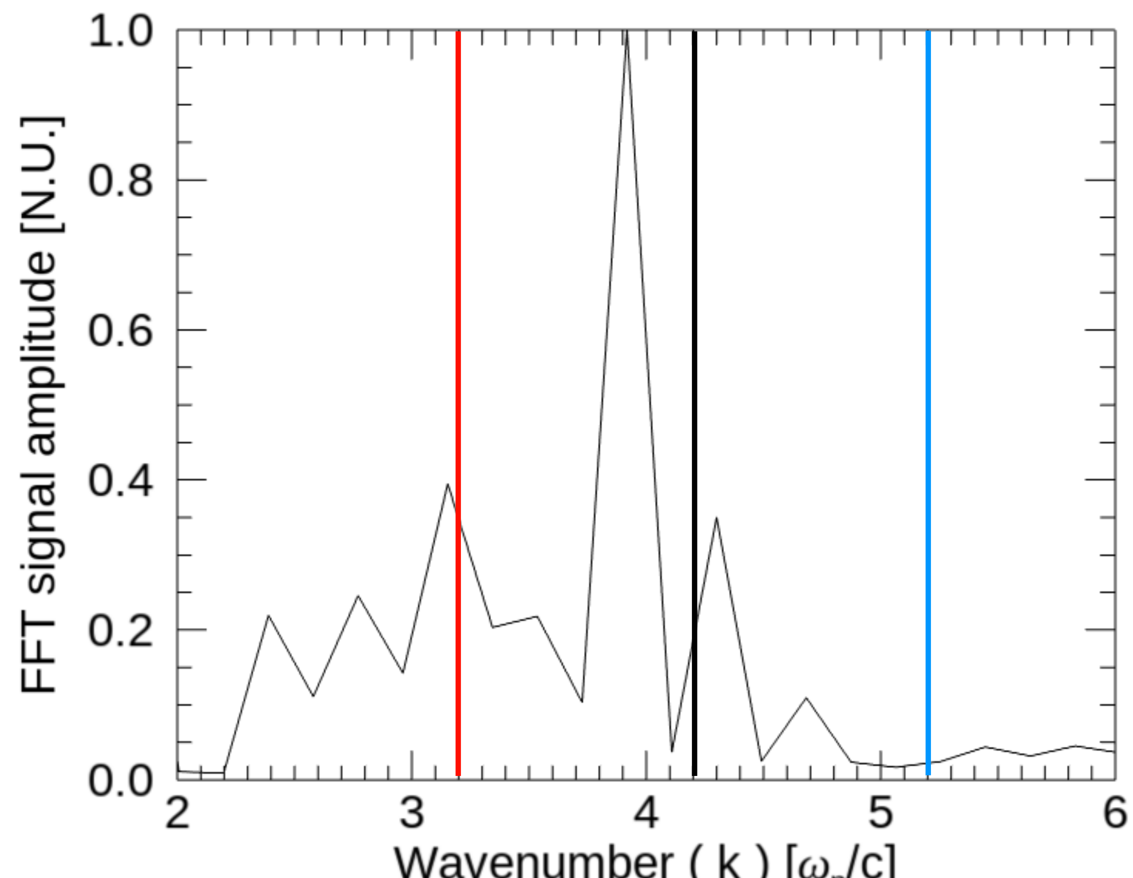
Transversely:
5500 cells
(30 per W_0)

Self-modulation stokes shift appears in field spectra

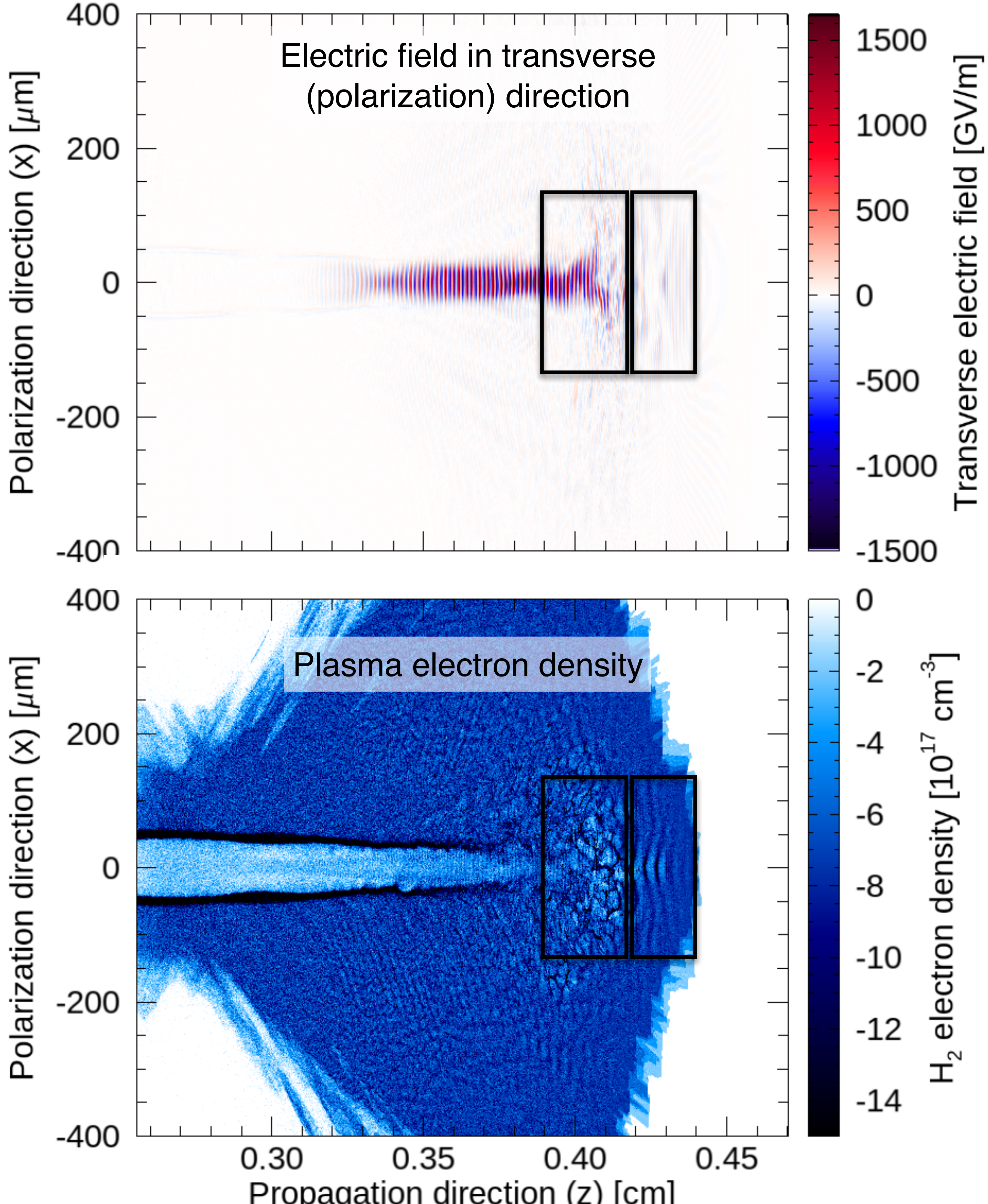


(Spectra of the field in polarization direction taken for each transverse slice, r_i, and then averaged over r_i, within black box region)

Fundamental	Stokes	Anti-stokes
k_0	$k_0 - k_p$	$k_0 + k_p$
4.2 k_p	4.2 k_p	5.2 k_p

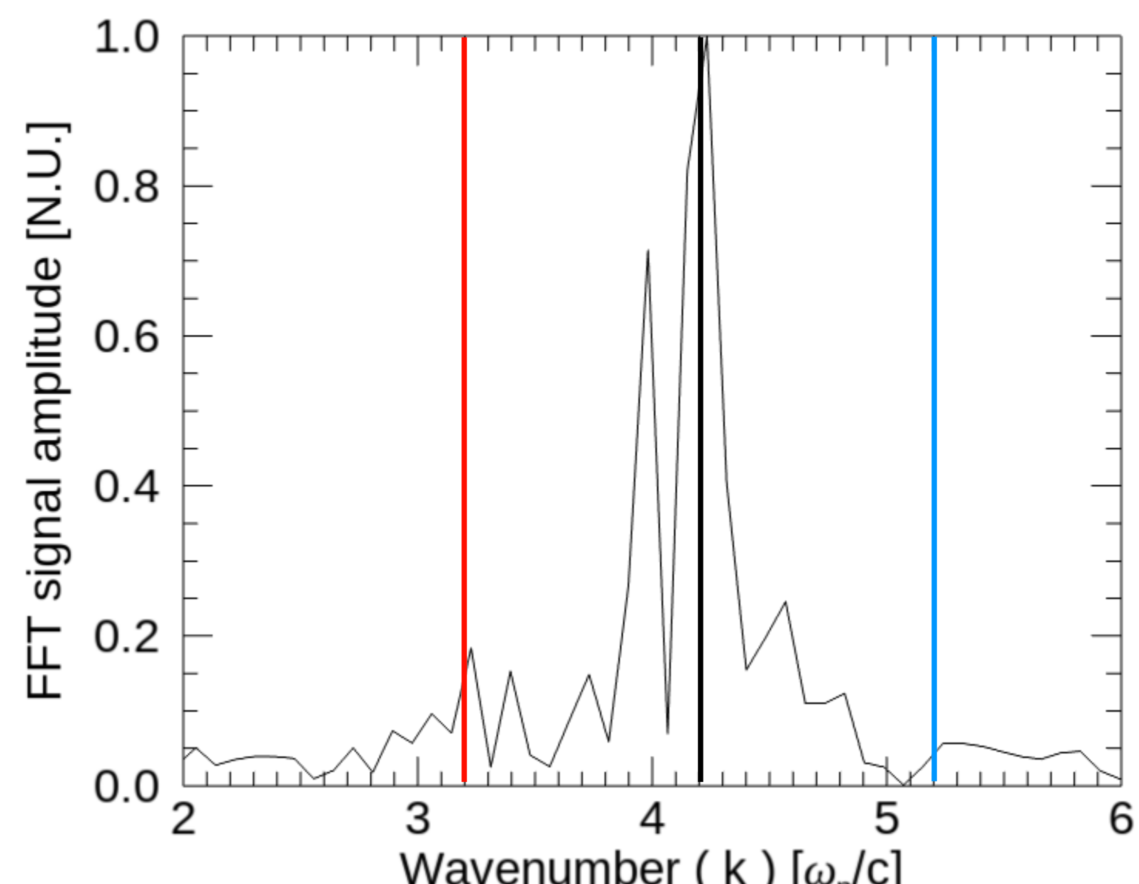


Self-modulation is followed by non-linear “hosing-like” phenomena



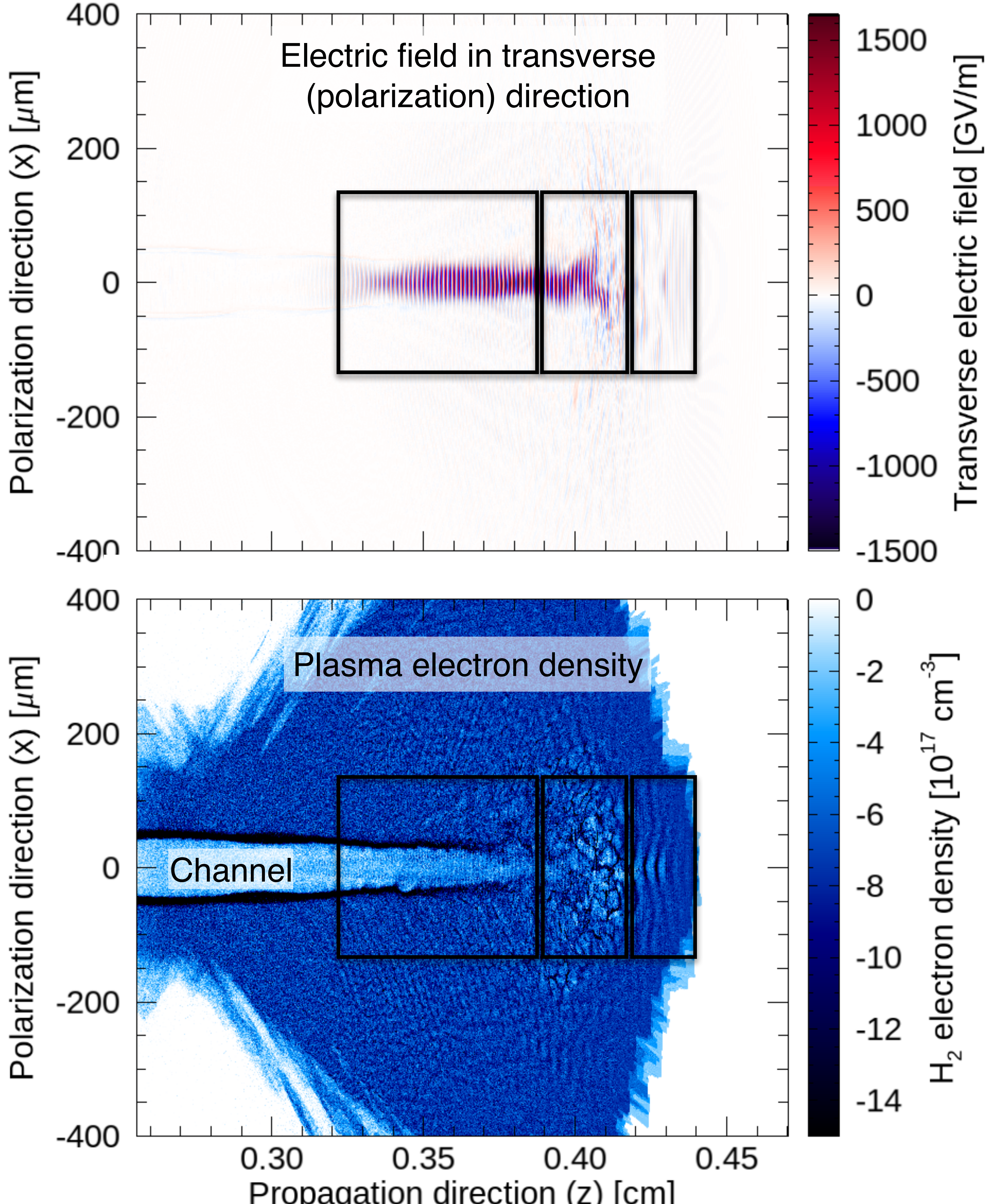
The “hosing-like” phenomena contributed to peaks between fundamental and stokes/ anti-stokes shifts (clearer at end of run)

Fundamental	Stokes	Anti-stokes
k_0	$k_0 - k_p$	$k_0 + k_p$
4.2 k_p	4.2 k_p	5.2 k_p



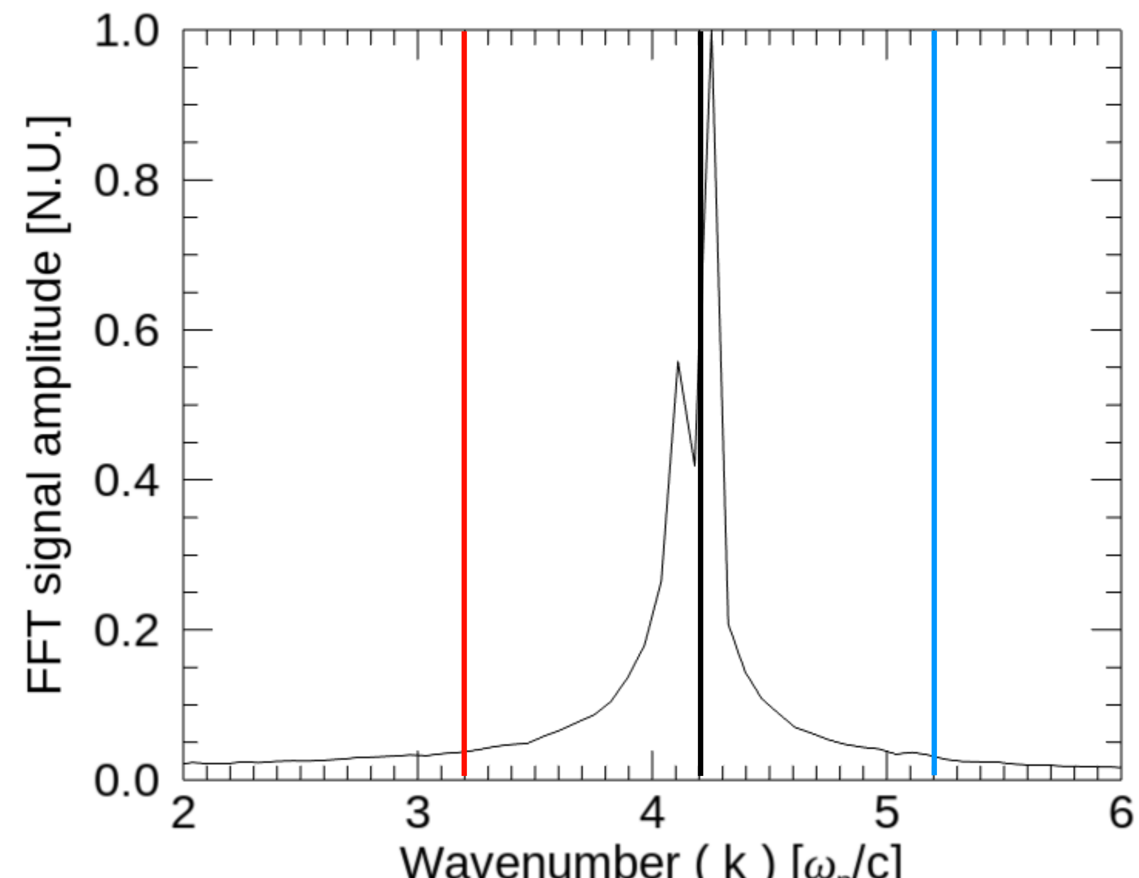
J. Yan et al. IEEE proceedings AAC 2018

Back of laser is guided in plasma depleted channel



Inside the plasma channel depleted of ions and e-s the laser wavenumber shifts are small

Fundamental	Stokes	Anti-stokes
k_0	$k_0 - k_p$	$k_0 + k_p$
4.2 k_p	4.2 k_p	5.2 k_p



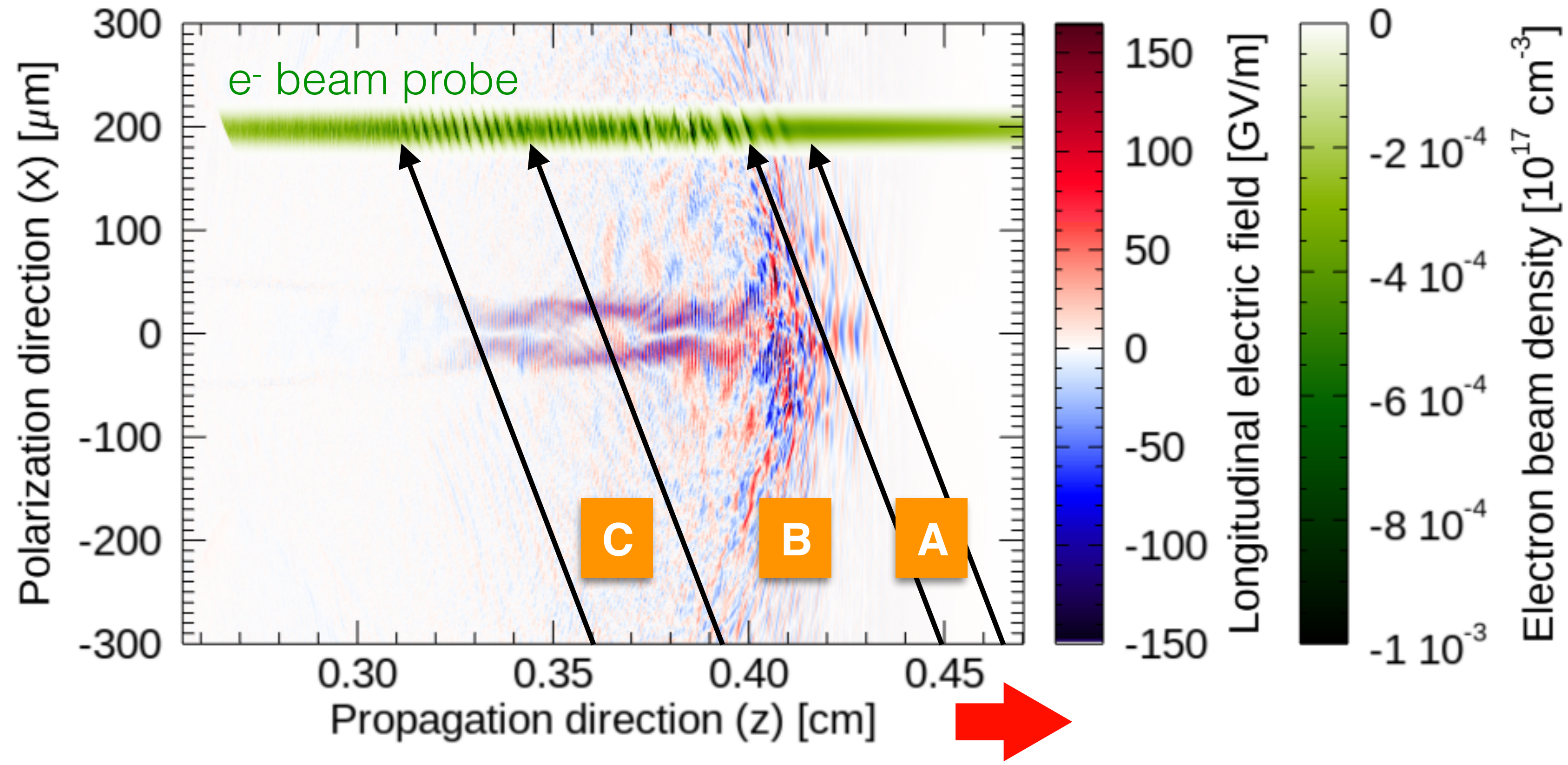
e^- beam modulations are characteristic of each interaction regime

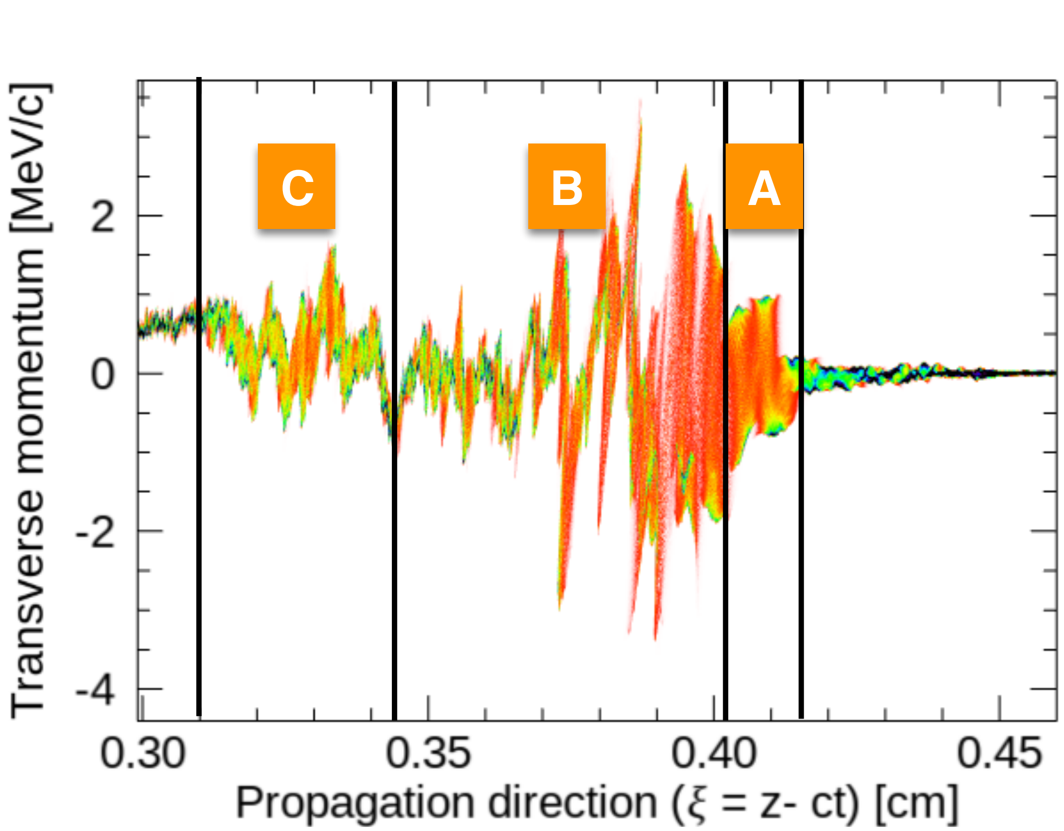
Stony Brook University

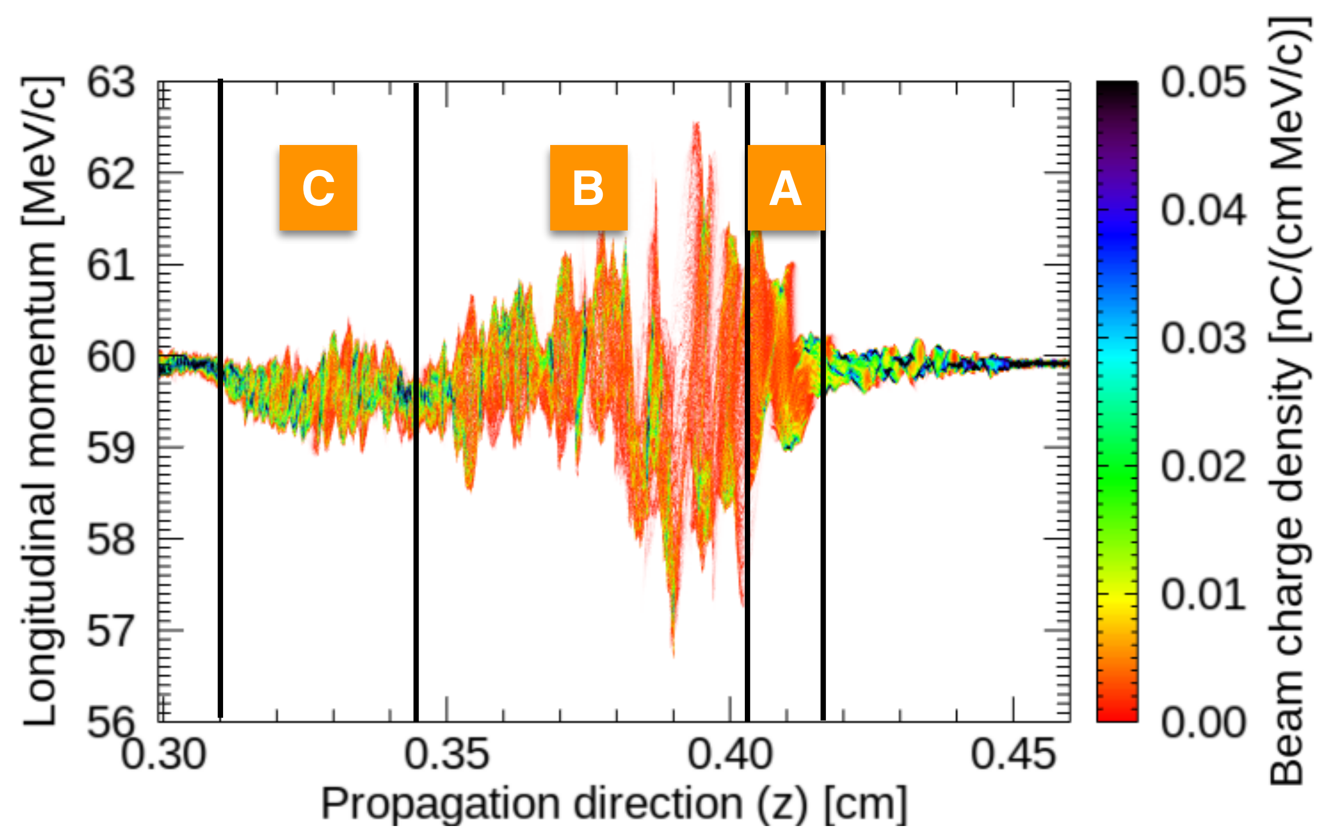
A In region of laser self-modulation e-beam shows structures at $\approx \lambda_p$

B "hosing-like" interaction leads to irregular beam perturbations, as hosing evolves in time and along the laser (from wave-breaking slice towards laser tail)

C Probe beam is modulated at $\approx \lambda_0$

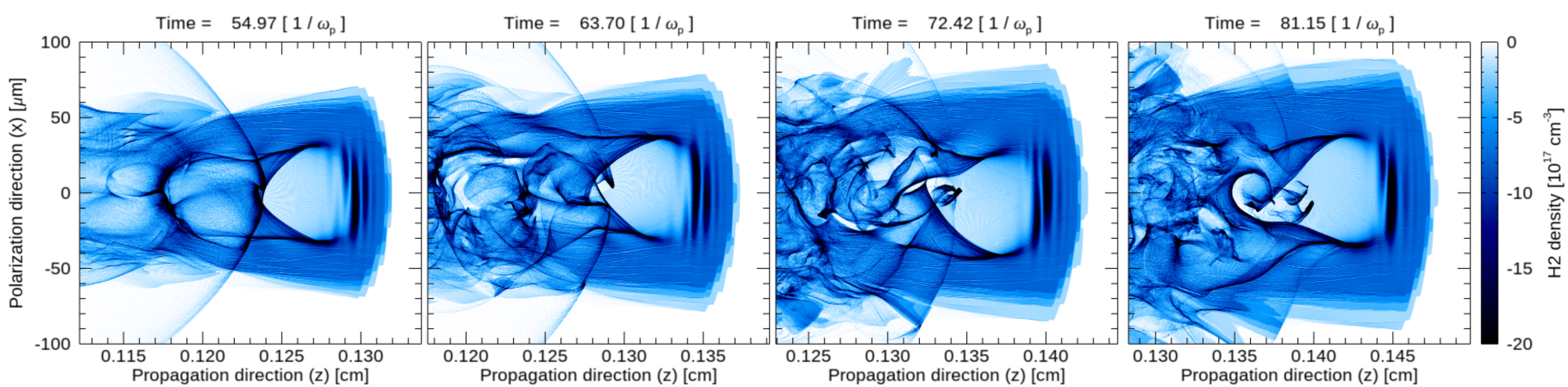






Electron transverse probing will enable time-resolved study of plasma structure evolution such as

- Evolution of particle injection in LWFA
- The study of hosing, which is in particular observed in simulations of ultrashort (<0.2 ps) CO_2 LWFA



τ =0.1 ps, a_0=4.3, n_e=7.5 e17

ATF **AE-93 and AE-95** Collaboration

J. Yan, P. Kumar, I. Petrushina, R. Samulyak, Y. Jing, V. N. Litvinenko and N. Vafaei-Najafabadi — @ Stony Brook University

P. Kaur, I. V. Pogorelsky, M. Babzien, K. Kusche, C. Cullen, M. Polyanskiy, M. Fedurin, R. Kupfer, M. Palmer — @ Brookhaven National Laboratory

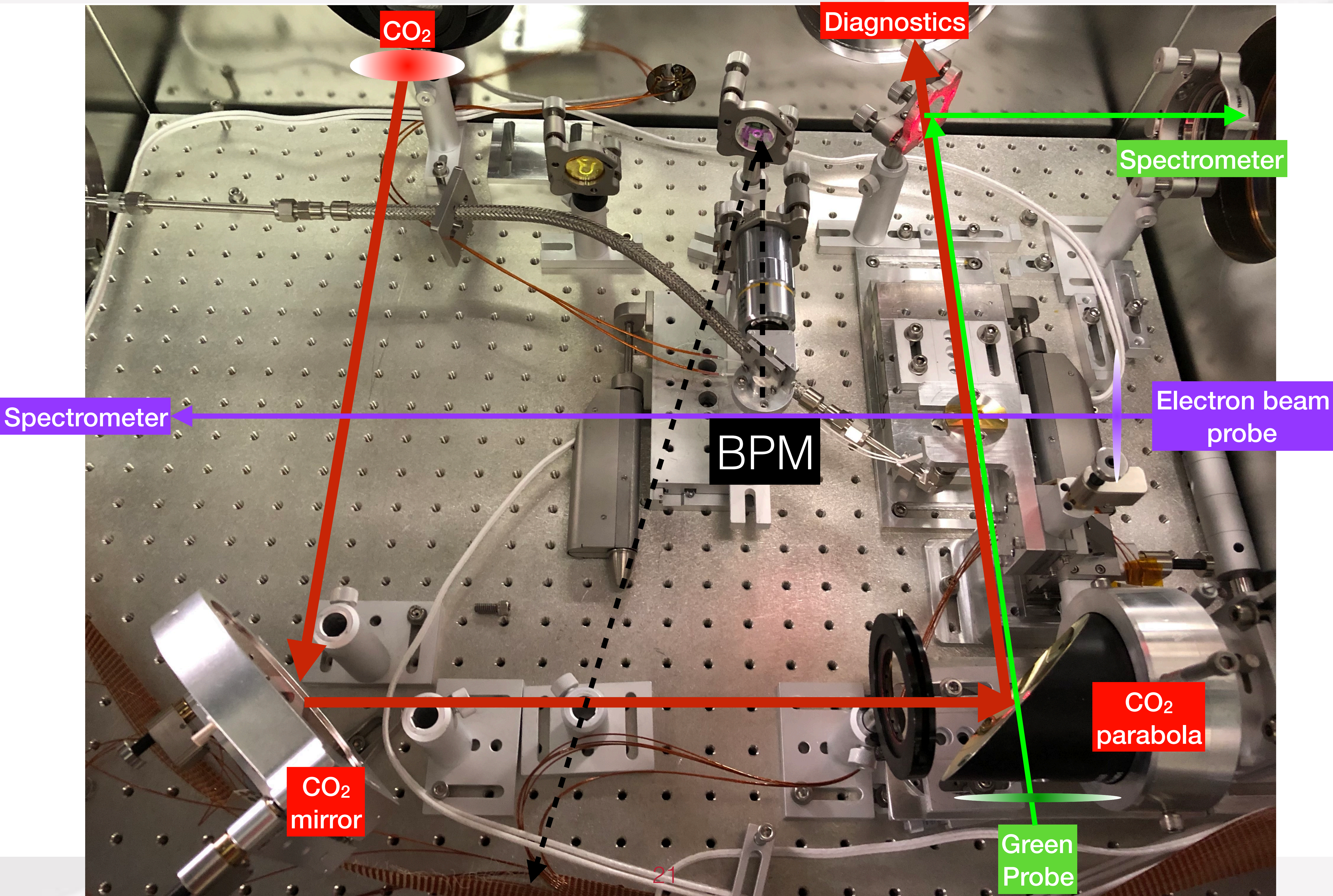
R. Zgadzaj, M. Downer — @ University of Texas at Austin

Acknowledging funding from DOE Grant No. DE-SC0014043

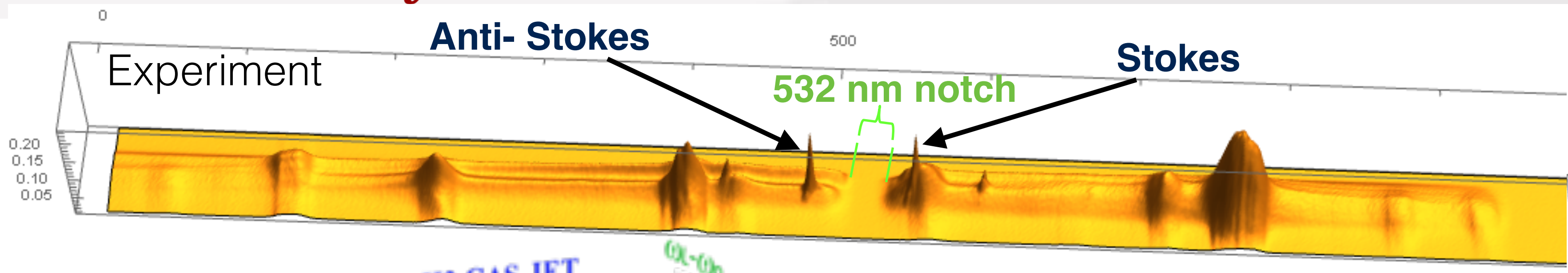
CORI@NERSC facility, operated under Contract No. DE-AC02-05CH11231

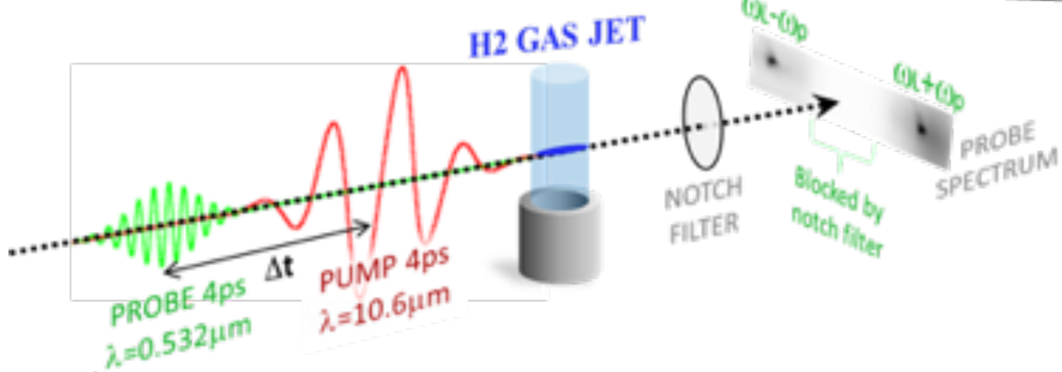
Stony Brook University

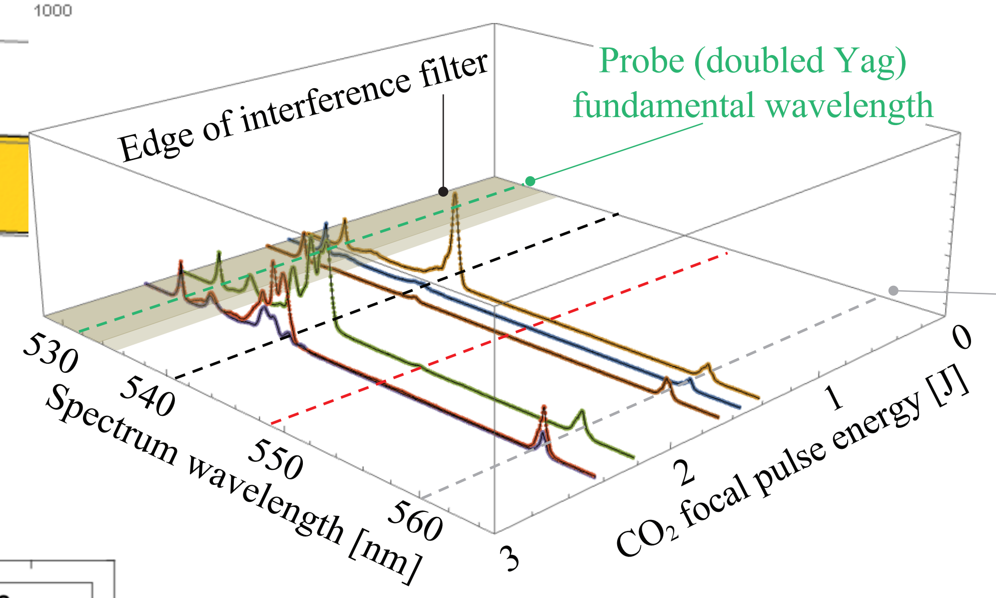
Experimental Layout

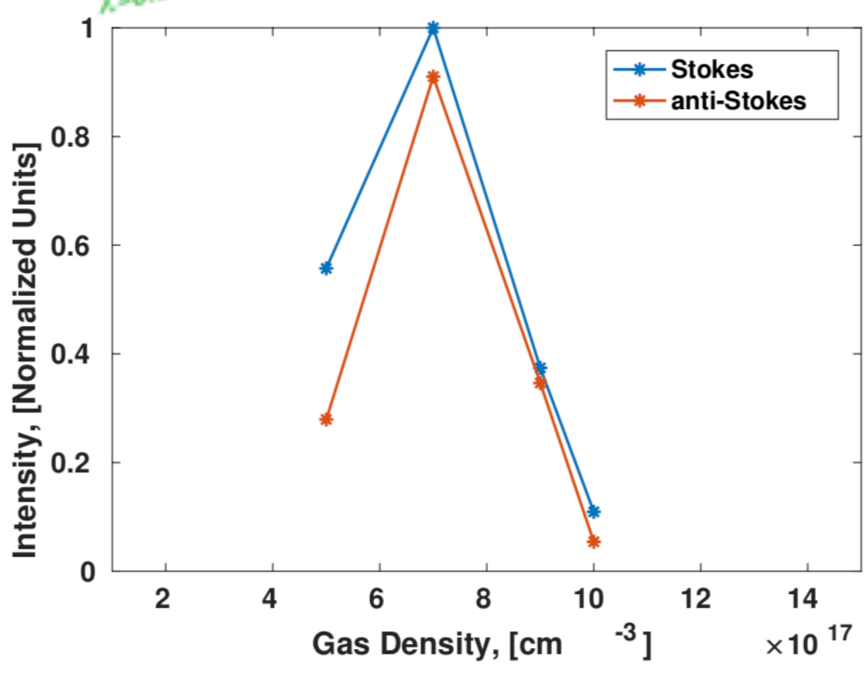


Recent Results

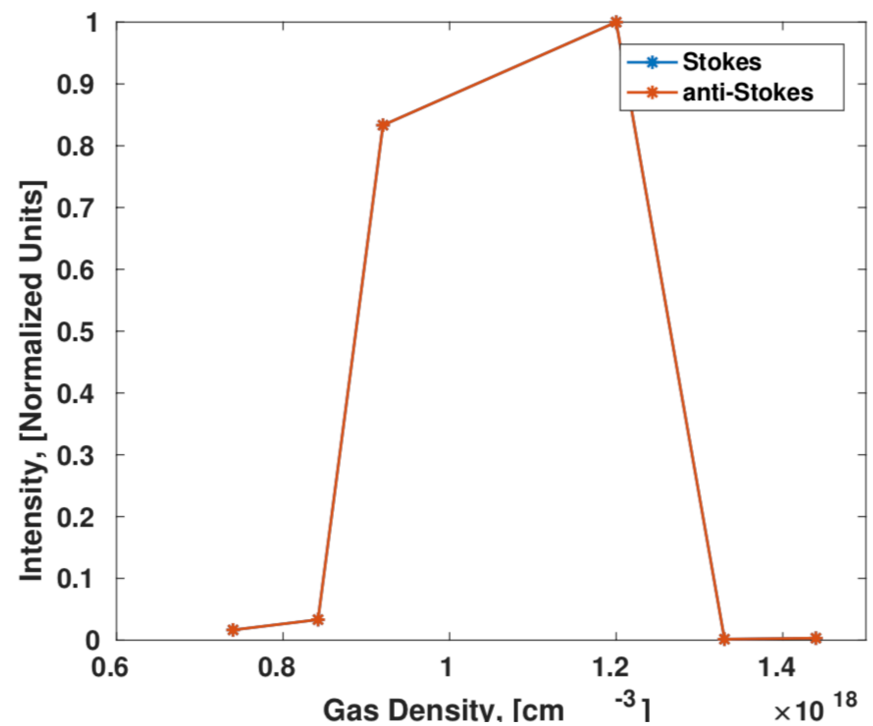








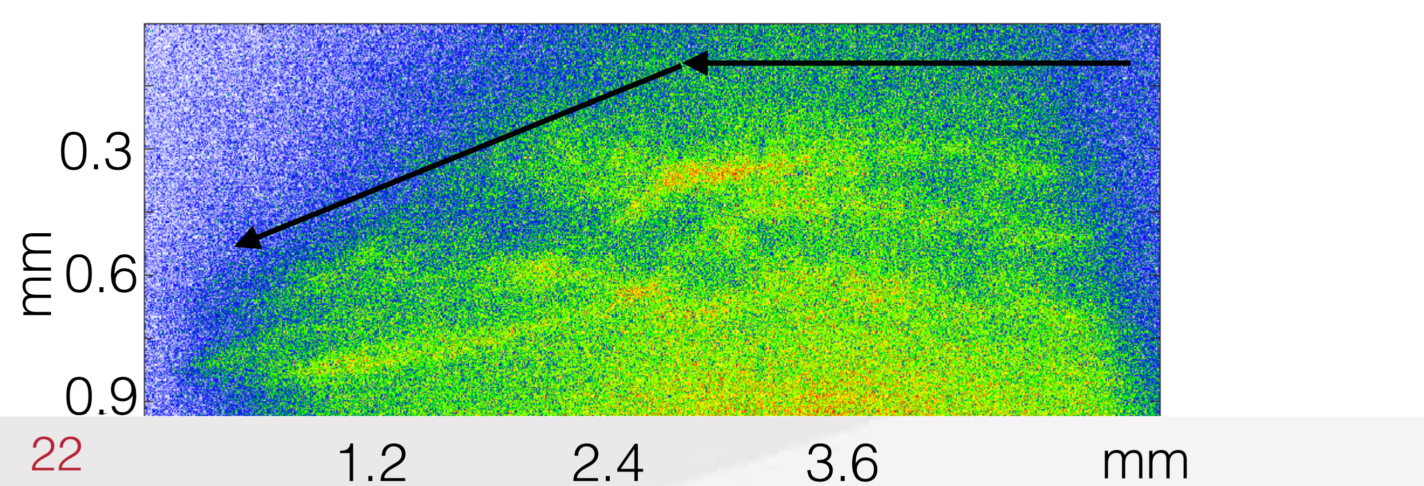
(a) Simulation



(b) Experiments

P. Kumar, et al., PoP **26** 083106 (2019)

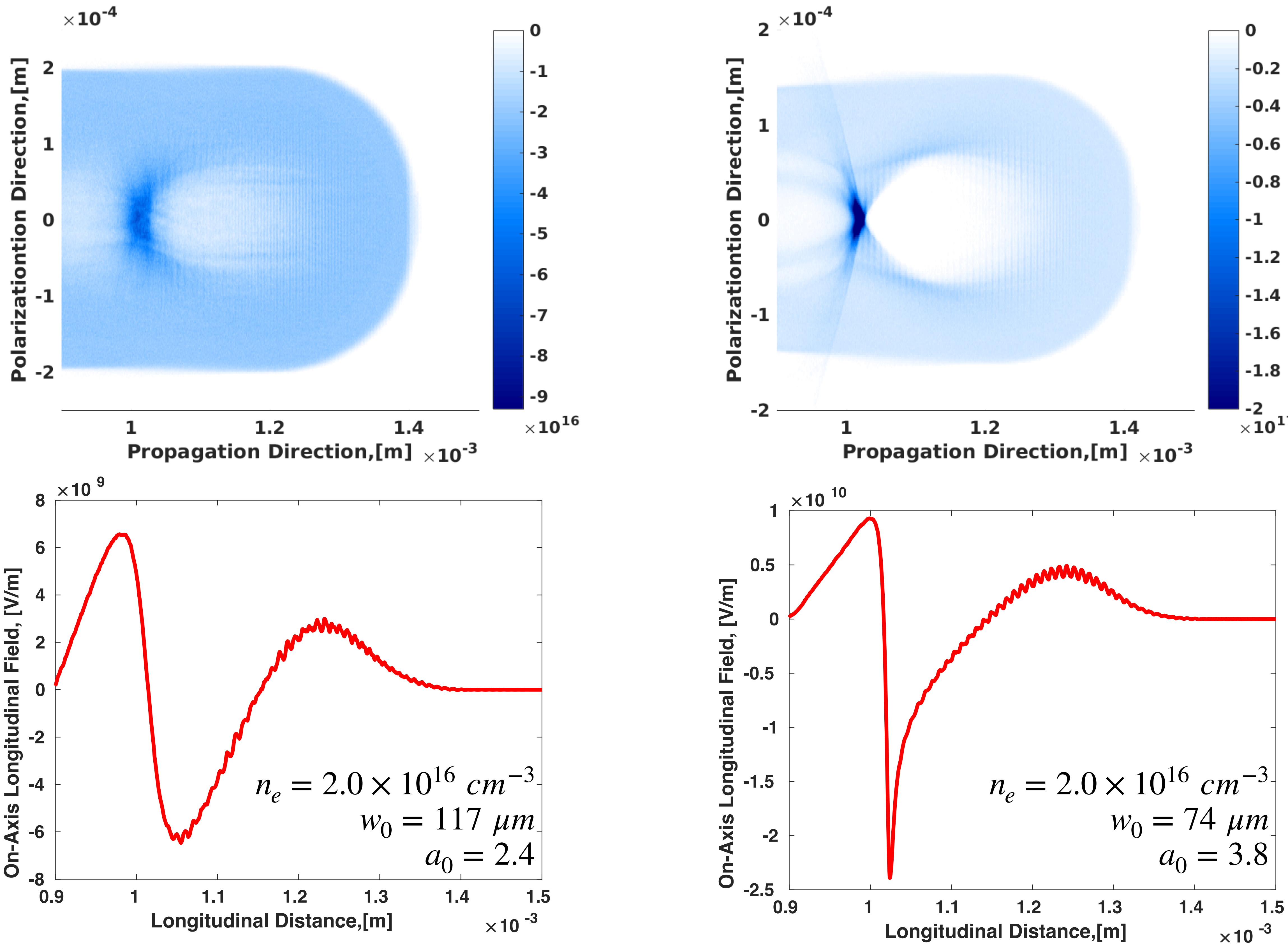
Preliminary image from the BPM on 1 ps electron beam probing of PWFA



Stony Brook University

The End

20 TW, 0.5 ps Matched/Unmatched Comparison



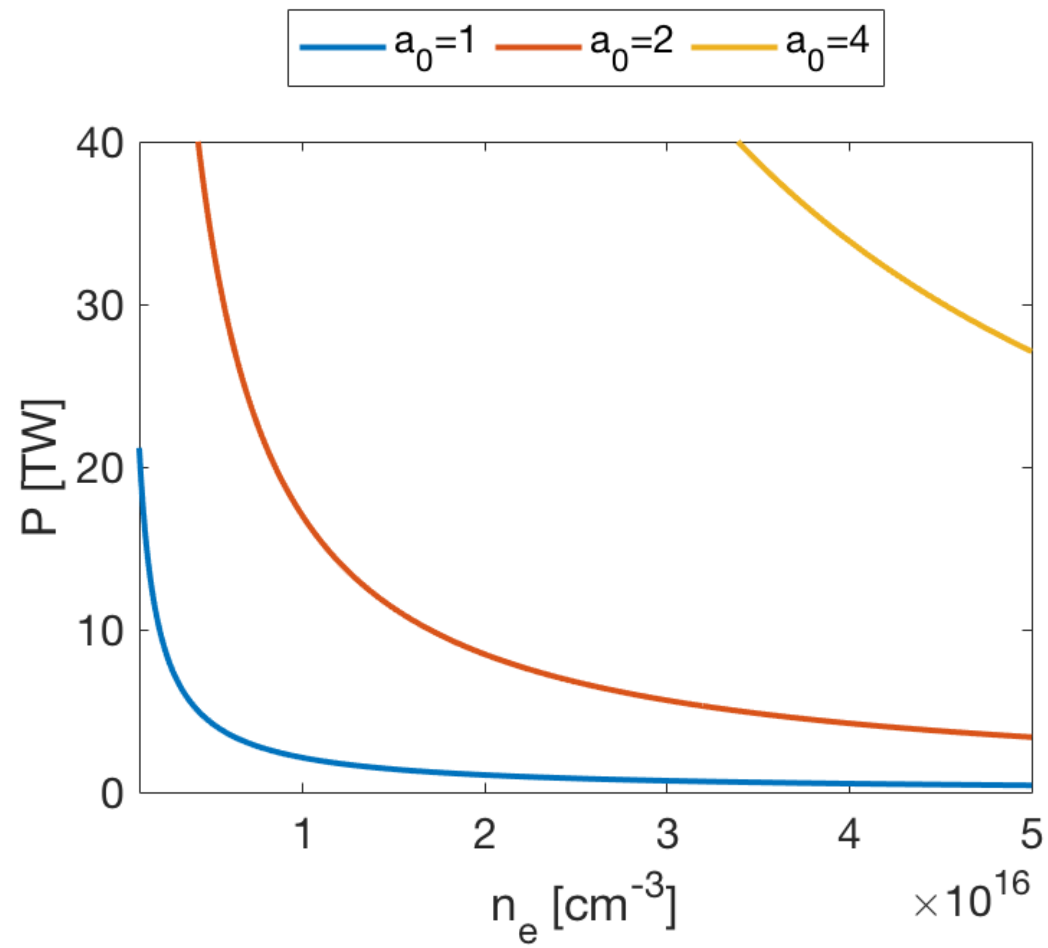
Laser Power Constraint

<u>Transverse Matching:</u>
"Self propagation of the laser in the wakefield with little transverse modification"

Condition for laser power

$$P/P_c = (a_0/2)^3$$

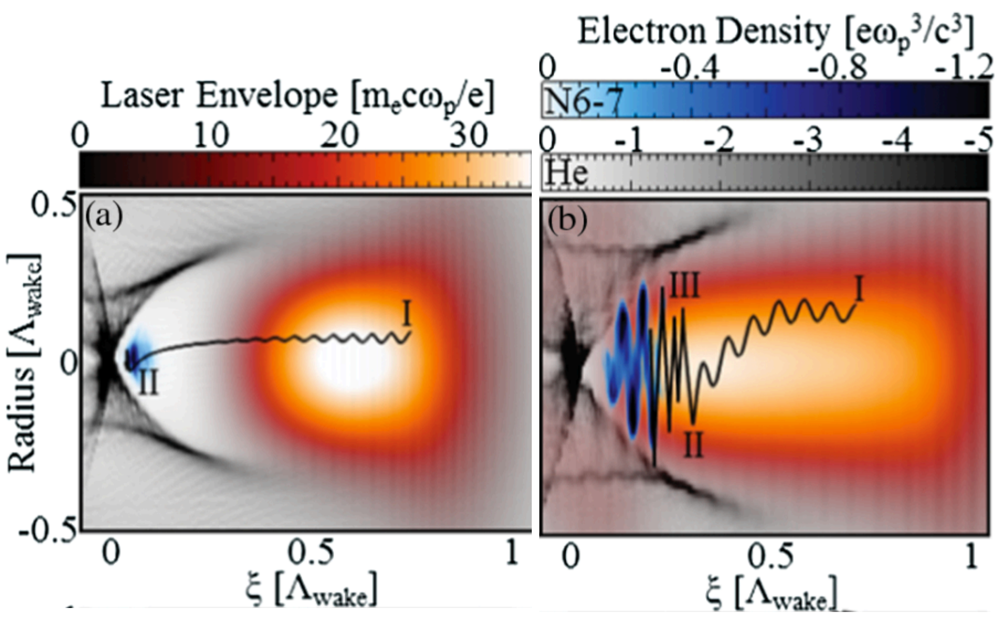
$$P_c[GW] = 17\left(\omega_0/\omega_p\right)^2$$

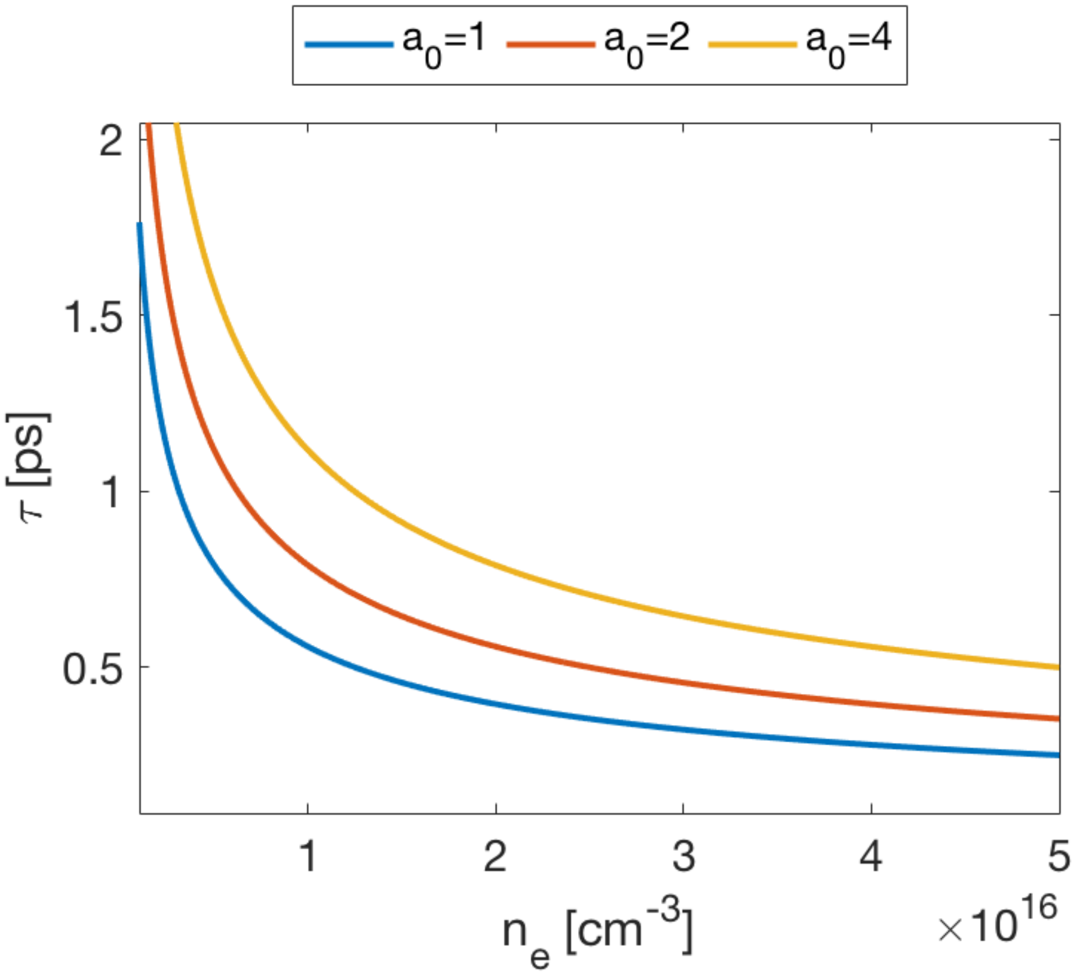


For a stable wakefield, the laser power has to be greater than the critical power for self-focusing

W. Lu, et al., *PRSTAB* **10** (2007): 61301

Pulse Length Constraint





Pulse length has to ideally be less than half of the length of the wake to avoid interaction between laser and accelerated electrons

$$T_p = \frac{\omega_p \tau_{laser}}{2\pi {a_0}^{1/2}} < \frac{1}{2}$$

Matched pulse gets smaller at higher density

J.L. Shaw, *PPCF* **56** (2014): 084006.
J.L. Shaw, *PRL* **118** (2017):064801.