CO2-laser-driven laser-wakefield acceleration experiments at Brookhaven's Accelerator Test Facility

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J. Yan, S. Kongtawong, *V. Litvinenko*
P. Kumar, *R. Samulyak* - *Stony Brook University*

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

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

W. Lu - *Tsinghua University, Beijing*

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CO2-laser-driven laser-wakefield acceleration experiments at Brookhaven's Accelerator Test Facility

Accelerator Test Facility (ATF):

- 70 MeV, sub-ps, 3kA S-band linac
- TW, 10μm few-ps CO_2 laser
- fs synchronization

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

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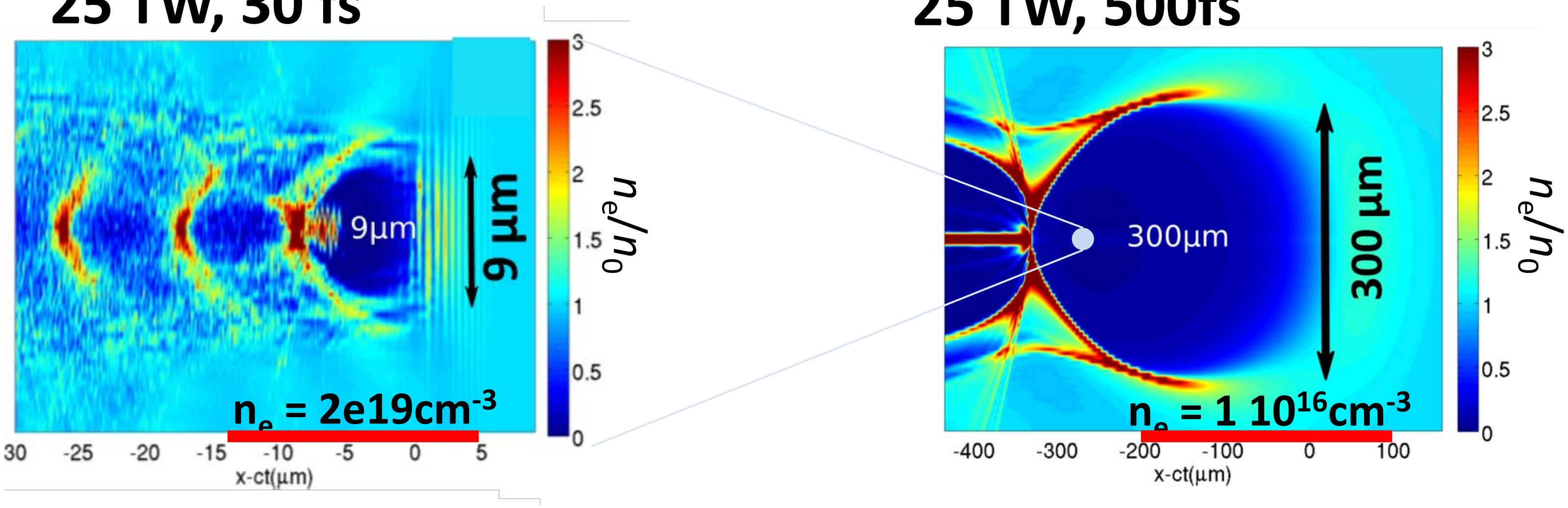
injection with ΔE/E ~ 0.1% from external linac or μm-focused UV ionizing laser

λ_{drive}= 0.8 μm (UT)
25 TW, 30 fs

λ_{drive}= 10 μm
25 TW, 500fs



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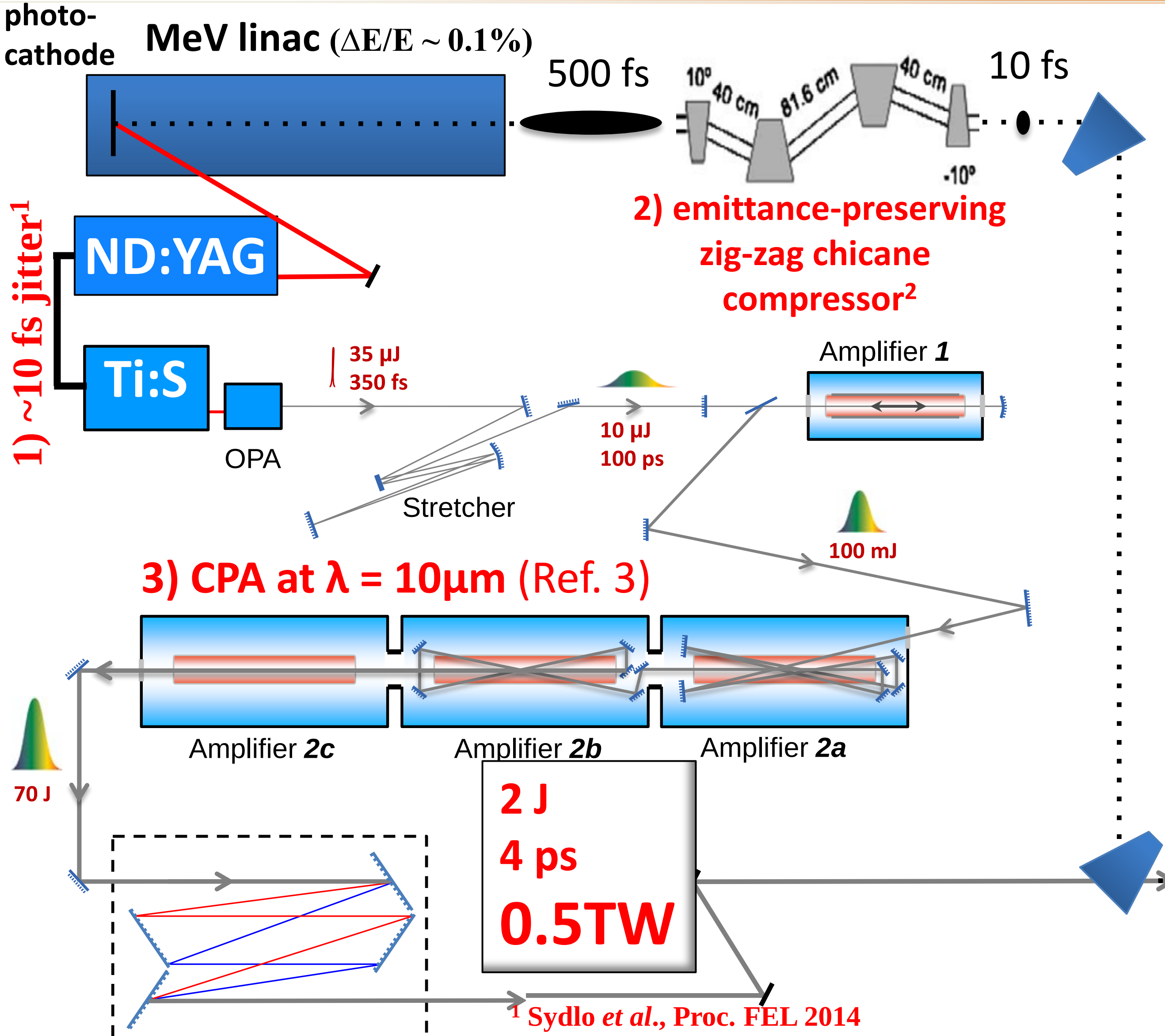
Our experiments use ATF's TW CO_2 laser, linac, & e-compression/synchronization capabilities



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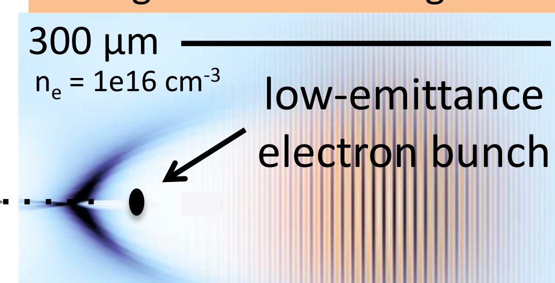
Large plasma bubbles
→ easy external injection,
→ high-resolution diagnostics



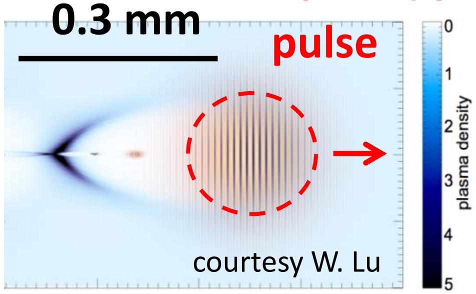
Bubble driven by 1μm, 25 TW laser in n_e = 1e19 cm^{-3} plasma:

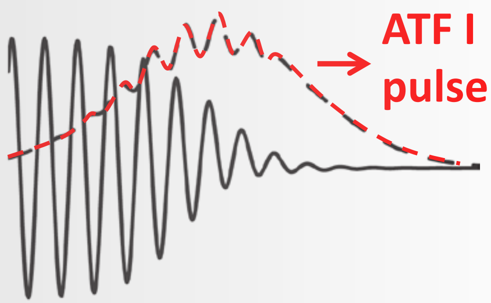
[1] Sydlo *et al.*, Proc. FEL 2014
[2] Litvinenko *et al.*, NIM A 557, 165 (2006).
[3] Babzien *et al.*, *Optica* (2016)

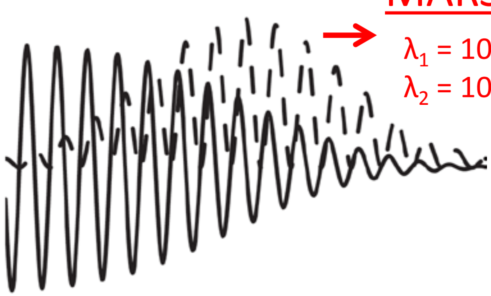
Upgraded ATF CO2 laser is needed for bubble LWFAs; meanwhile we study SM-LWFA with ATF I pulses

3 CO_2 LWFA experiments:

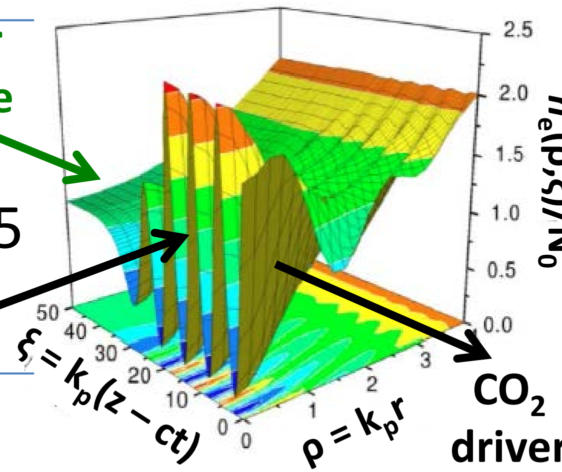
	n_e (cm^{-3})	τ (ps)	P (TW)
Bubble Regime LWFA	10^{16}	0.5	25
Self-Modulated LWFA	~10^{18}	4	0.5
Plasma Beat-Wave Accelerator	<10^{16}	300	0.2







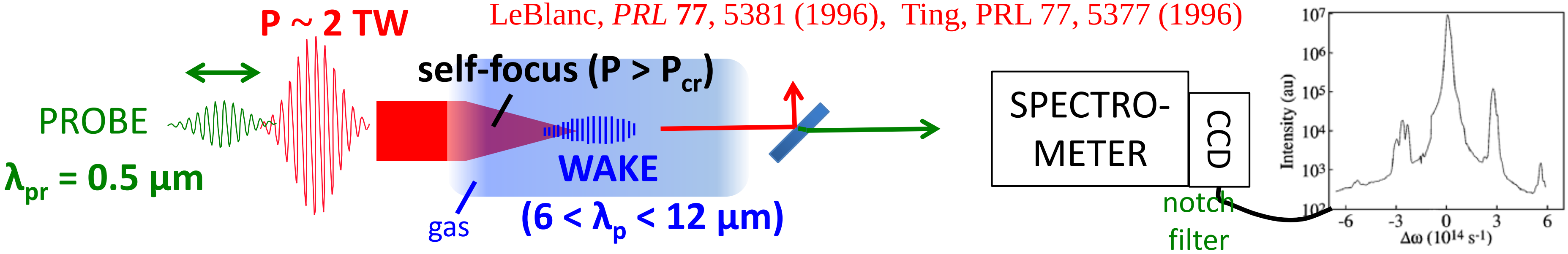
simulations:
N. E. Andreev *et al.*,
PR-STAB **6**, 041301 (2003)

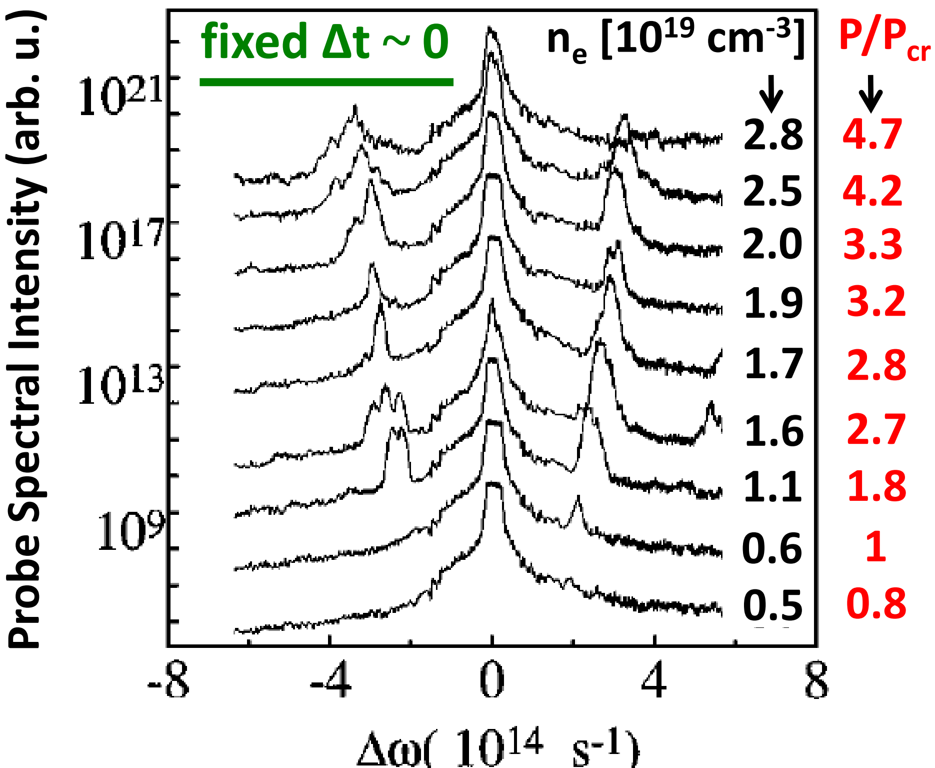


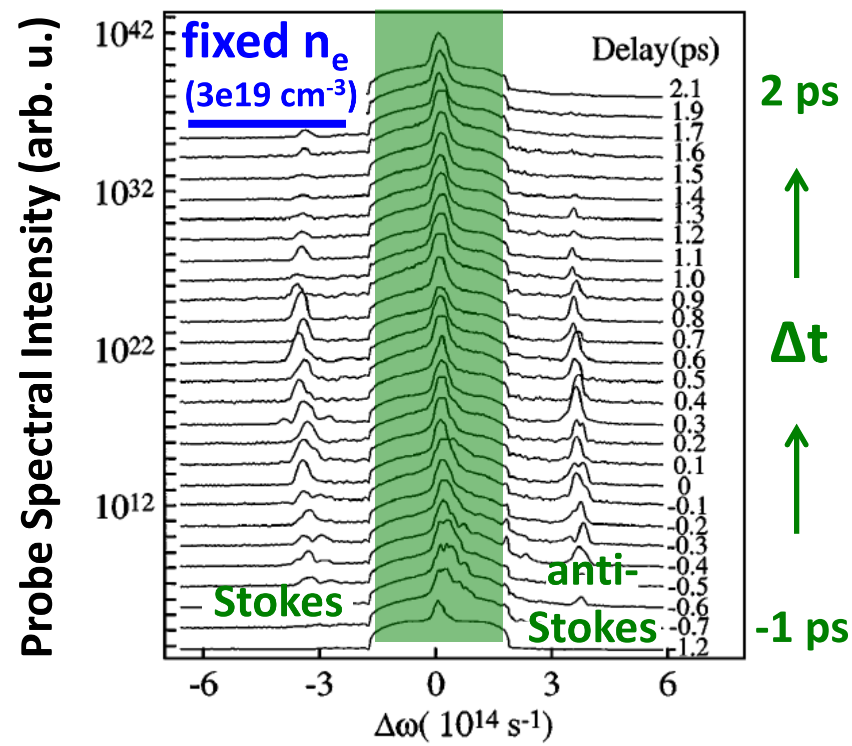
Clayton *et al.*, *PRL* 70, 37 (1992)

We modeled CO_2 SM-LWFA experiments after prior expts with $\lambda = 1$ μm, 400 fs drive pulses in $n_e \sim 10^{19}$ cm^{-3} plasma

LeBlanc, *PRL* **77**, 5381 (1996), Ting, PRL 77, 5377 (1996)







probe frequency shift:

$\Delta\omega = \pm\,\omega_p = (n_e e^2/\varepsilon_0 m)^{1/2}$

critical power for relativistic self-focusing:

P_{cr} [GW] = 17 (n_{cr}/n_e)

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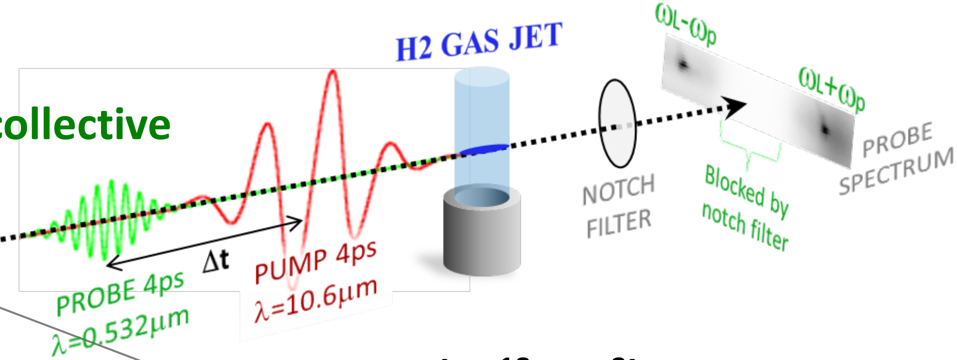
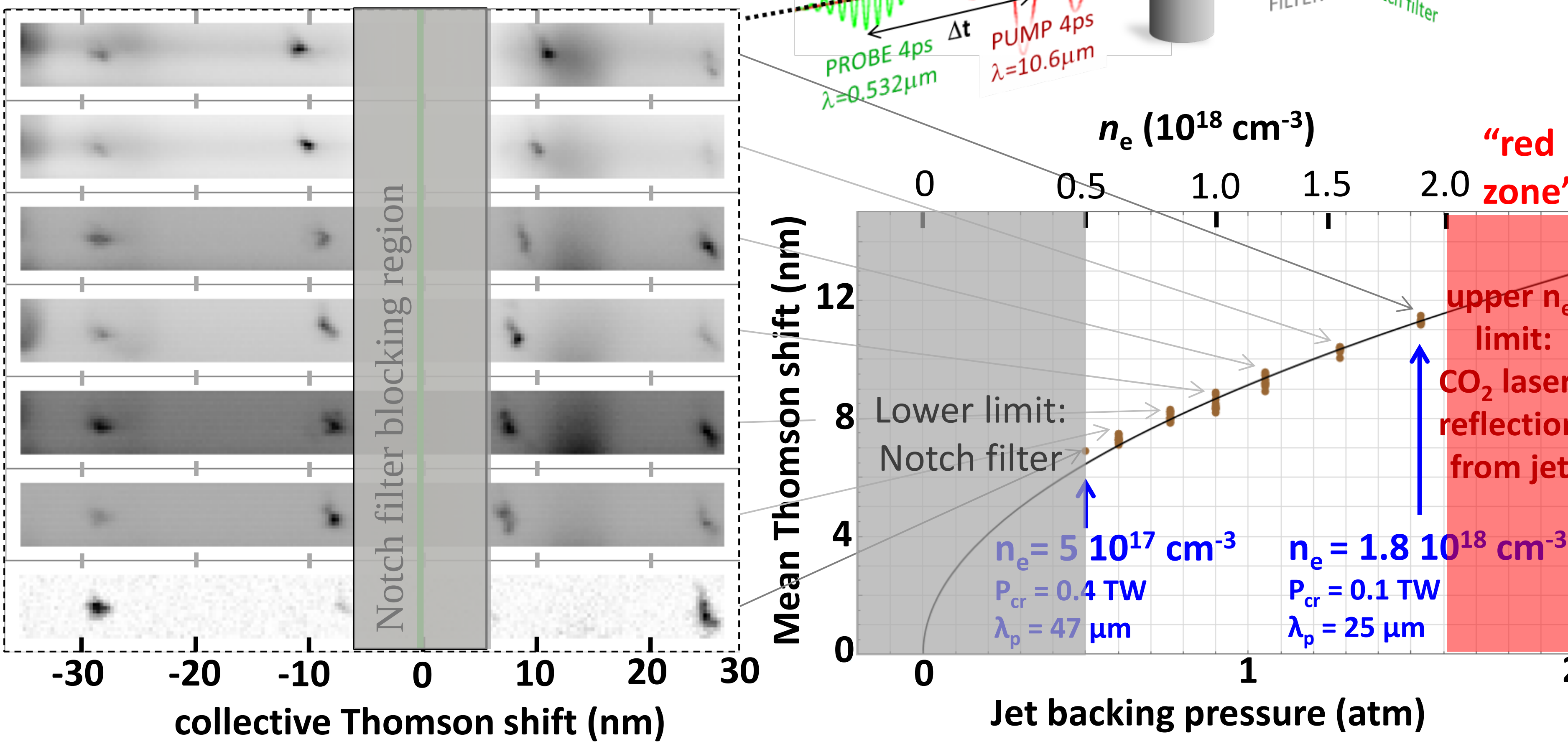
n_e-dependent probe spectral shifts

0.5 TW, 4 ps CO_2 laser pulse ($\lambda = 10\mu m$) drives SM-LWFA

CO_2 laser pulse drives SM-LWFA

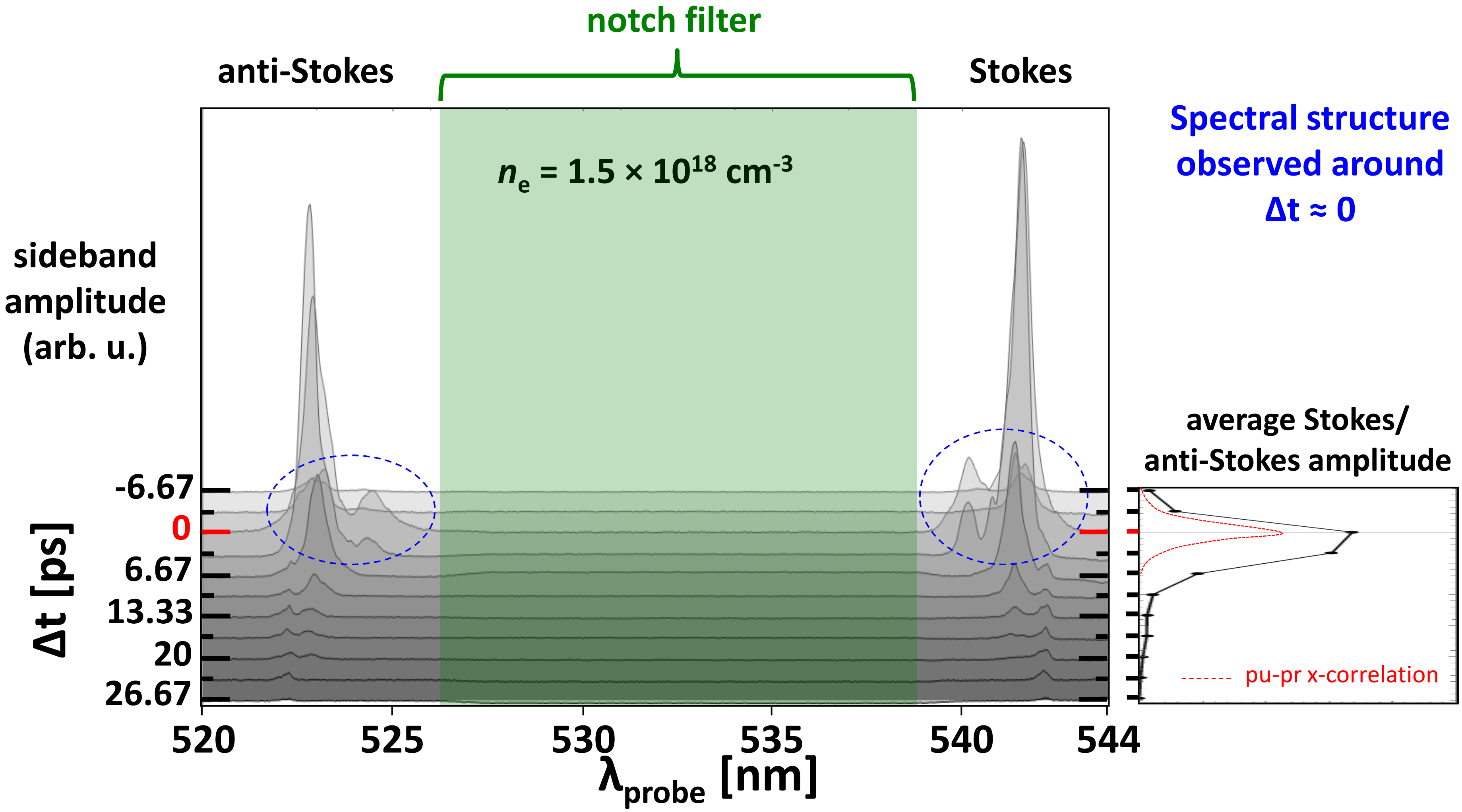
4 ps, 0.53 μm pulse probes wake via forward collective Thomson scatter as n_e , Δt and P_{CO2} vary.





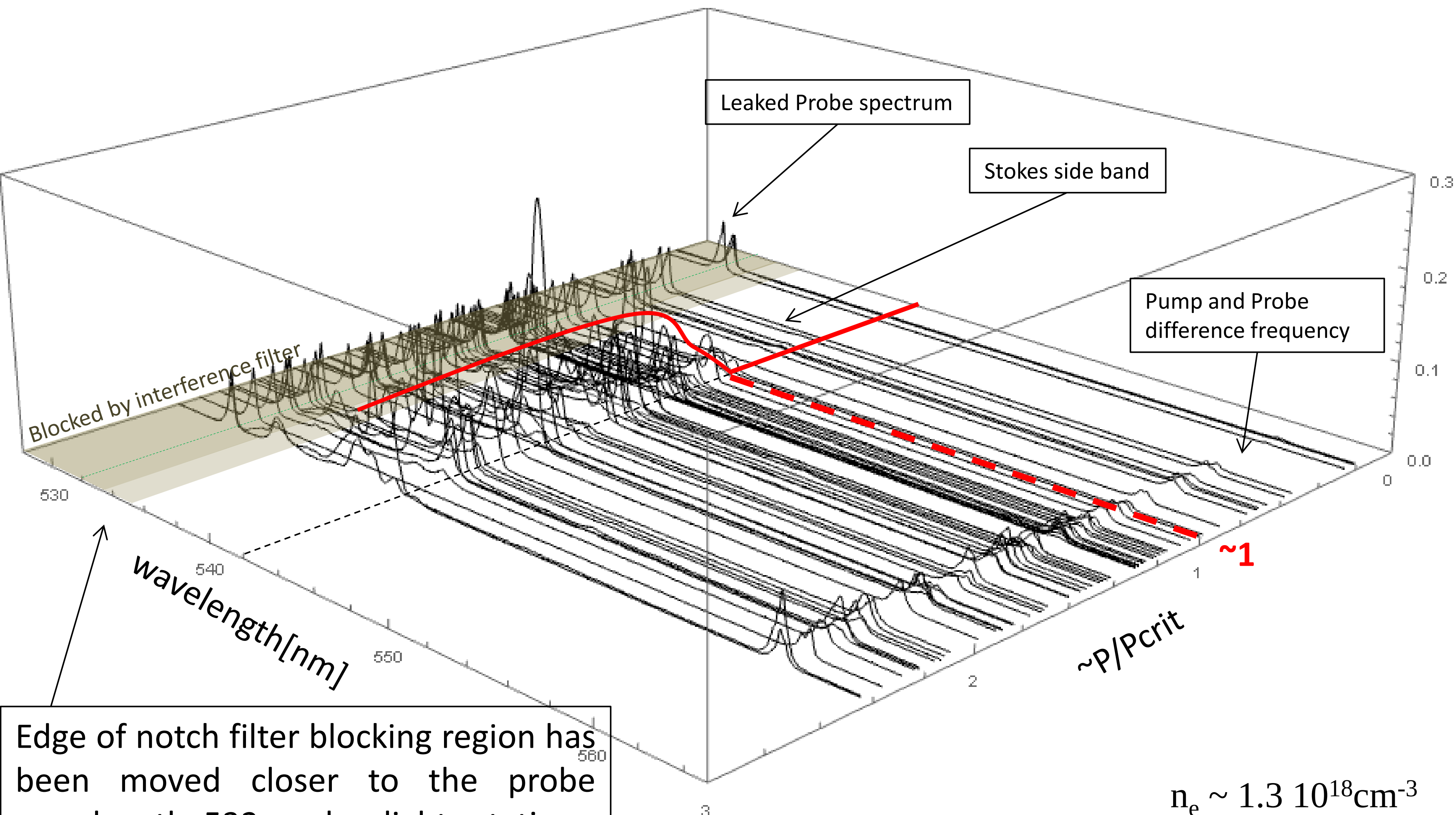
Δt-dependent probe spectral shifts show wake decays 90% in ~10 ps, remnants observable at Δt > 25 ps

J. Welch, *et al.*, "Observation of SM-LWFs driven by TW CO_2 laser," in prep. for *PR-Accel. Beams* (2019).



Spectral structure observed around Δt ≈ 0

Onset of self modulation is observed near P/Pcrit ~ 1



Edge of notch filter blocking region has been moved closer to the probe wavelength, 532nm, by slight rotation.

$n_e \sim 1.3\ 10^{18} cm^{-3}$

1st generation 3D OSRIS[1] PIC simulations confirmed 5 observations qualitatively ...

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TSINGHUA UNIVERSITY

Osiris 4.0

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(1) initial self-focusing

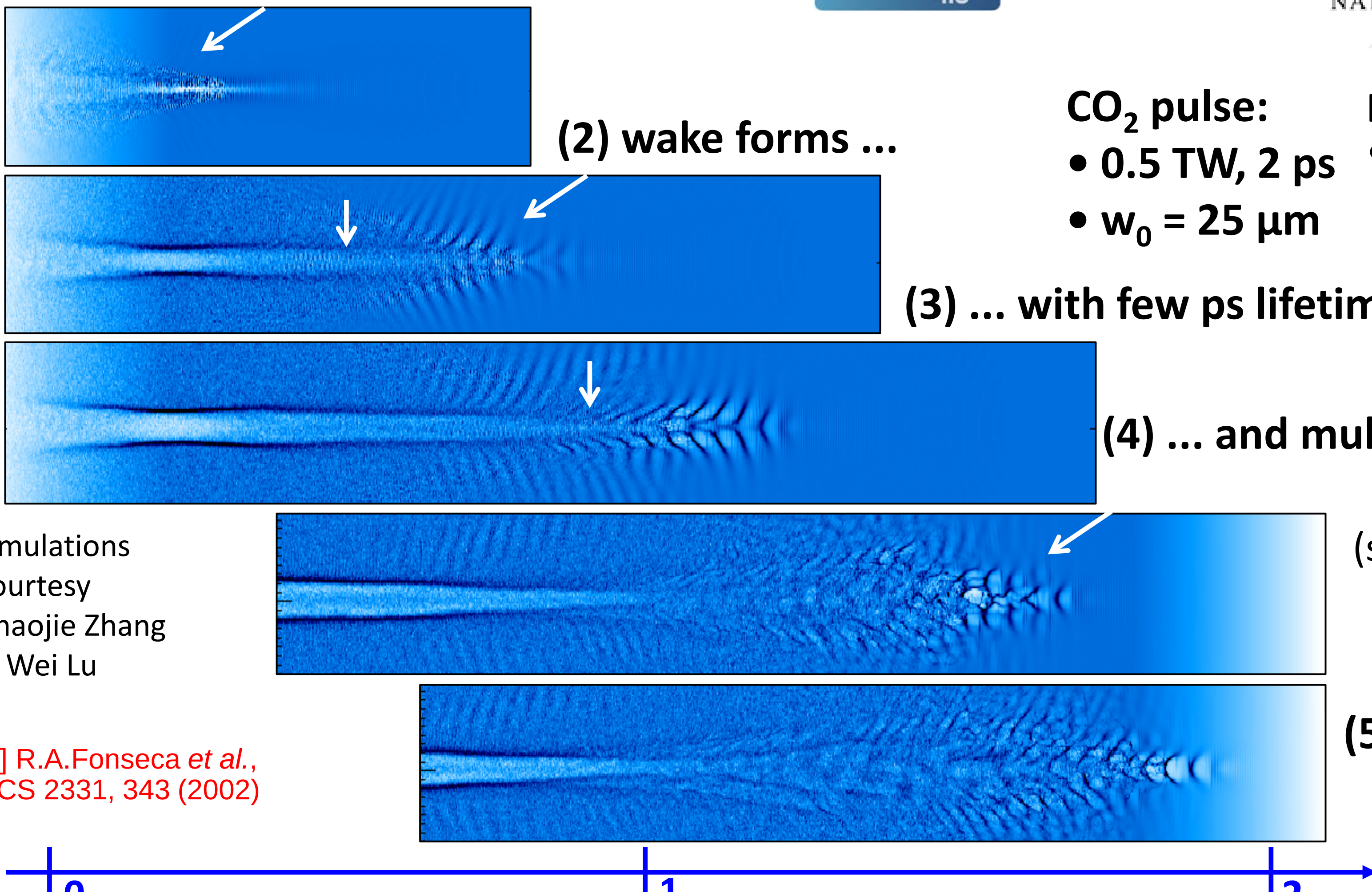
(2) wake forms ...

(3) ... with few ps lifetime

(4) ... and multiple oscillation frequencies

(source of side-band spectral structure?)

(5) no e- produced



CO_2 pulse:

- **0.5 TW, 2 ps**
- **w_0 = 25 µm**

plasma:

- **n_e = 6e17 cm^{-3}**

simulations courtesy Chaojie Zhang & Wei Lu

[1] R.A.Fonseca *et al.*, NCS 2331, 343 (2002)

... but did not study the pump or probe spectra structure

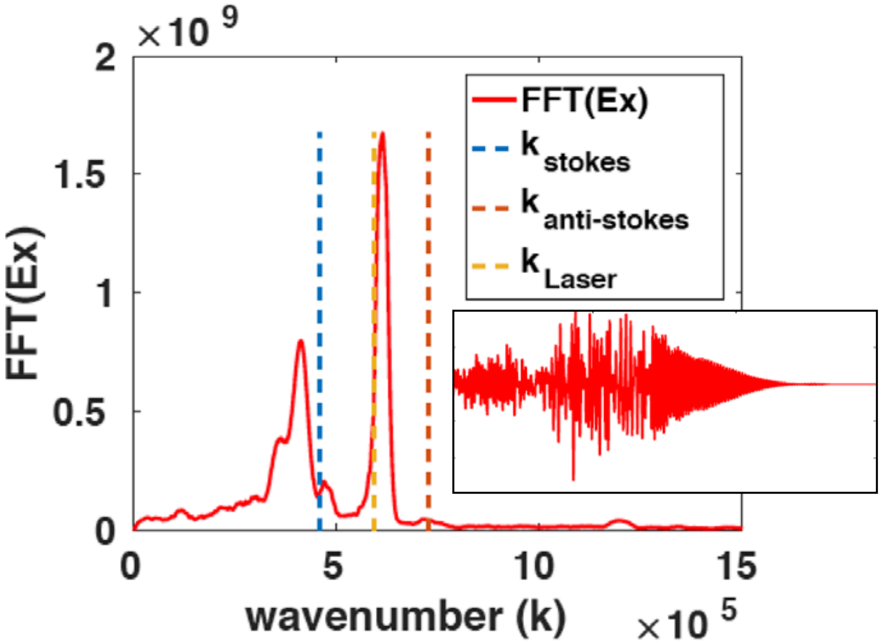
Ionization is critical to reproducing approximate Stokes/anti-Stokes symmetry[2]

Simulations using SPACE[1] code: P. Kumar, R. Samulyak, Stony Brook University

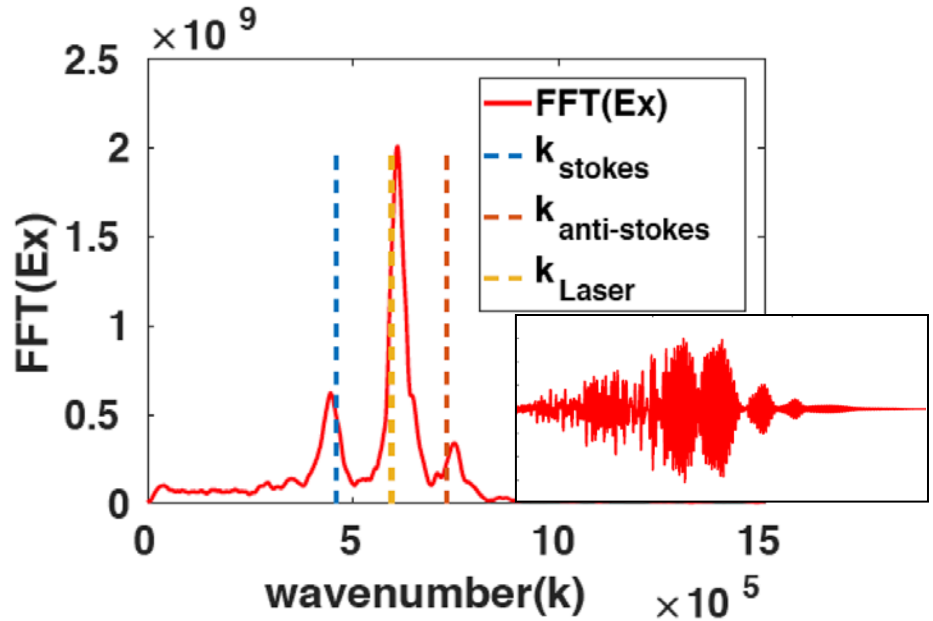
3D parallel, relativistic particle-in-cell code for simulating EM fields, relativistic particles, plasma & atomic processes

1. K. Yu, R. Samulyak, “SPACE code for beam-plasma interactions,” *Proc. IPAC*, 728 (2015)
2. P. Kumar, “Role of ionization in mid IR laser-plasma interaction simulations”, SUBMITTED

PRE-IONIZED PLASMA



DYNAMIC IONIZATON



- **Ionization seeds the forward Raman instability**

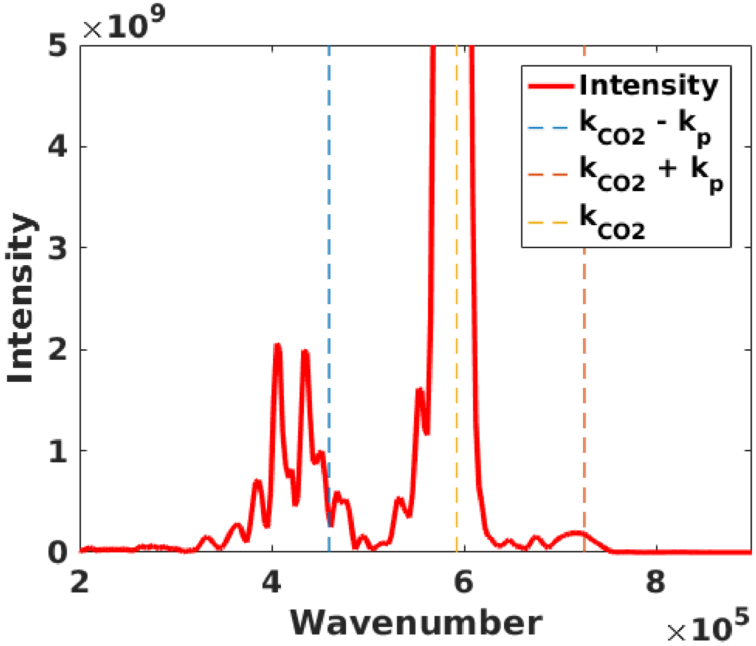
Pump and probe included in the SPACE code PIC simulation. Synthetic diagnostic.

Simulations using SPACE[1] code: P. Kumar, R. Samulyak, Stony Brook University

3D parallel, relativistic particle-in-cell code for simulating EM fields, relativistic particles, plasma & atomic processes

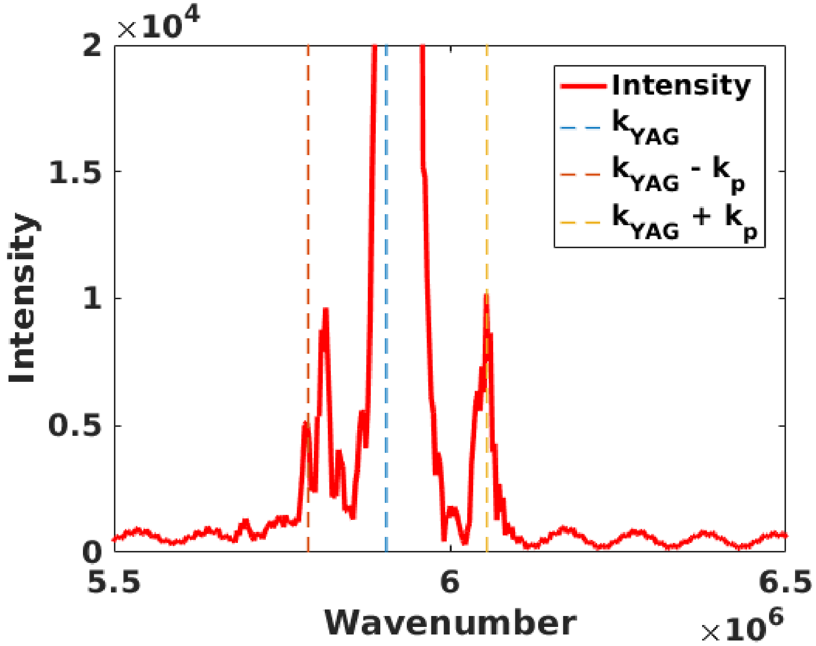
1. K. Yu, R. Samulyak, "SPACE code for beam-plasma interactions," *Proc. IPAC*, 728 (2015)

CO2 pump spectrum



Strong side band asymmetry in pump laser spectrum after interaction.

1064nm Probe spectrum

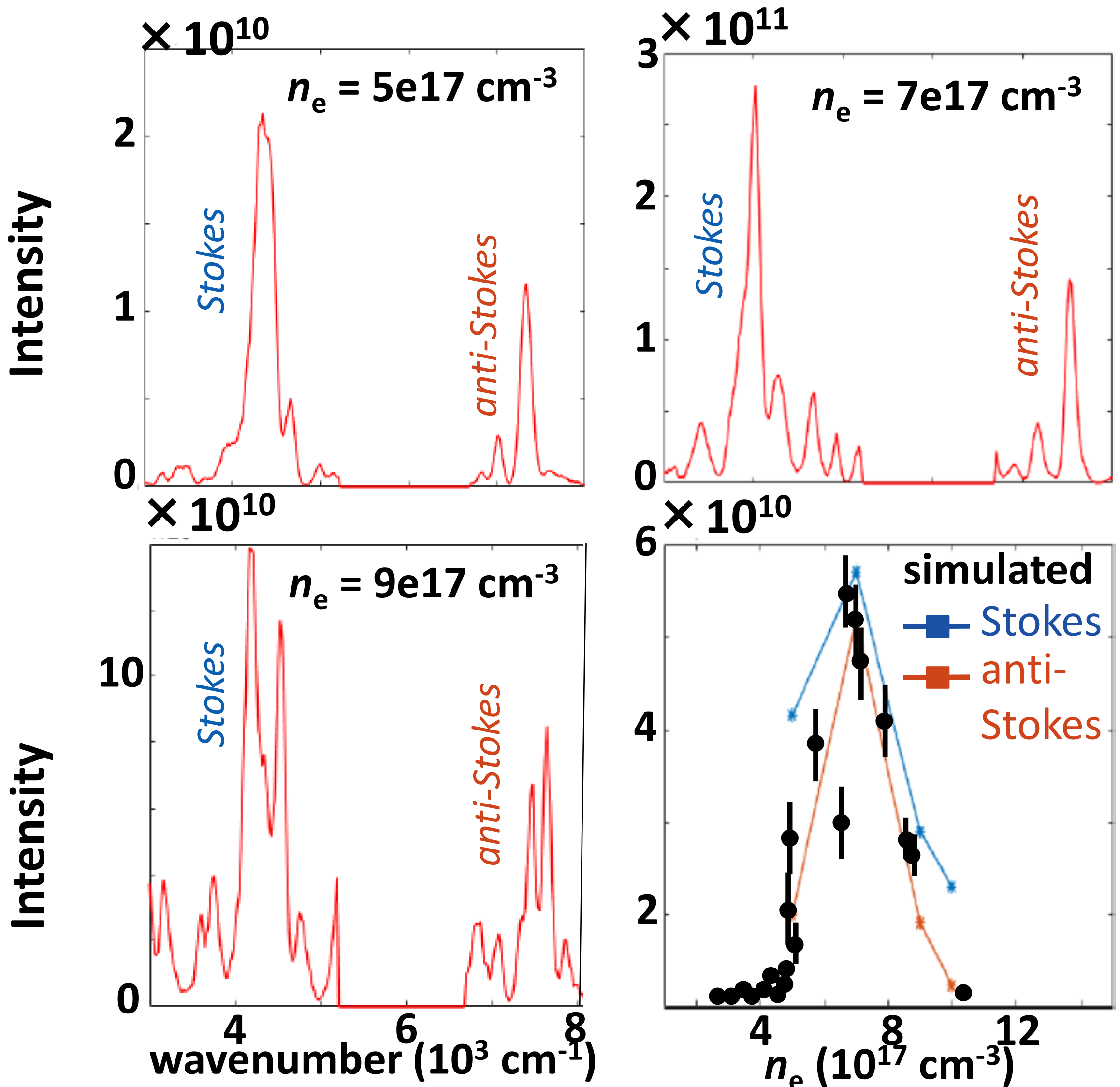


Probe side band structure is much more symmetric than in the pump spectrum.

This agrees with observations. Sidebands are symmetric in the data.

SPACE[1] simulations elucidated previously unexplained n_e-dependence of sideband amplitudes

Simulations: P. Kumar, R. Samulyak, Stony Brook University



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

- **At high n_e, the drive laser overfocuses, preventing sustained wake propagation.**
- **Spectral structure in sidebands agrees with observations.**

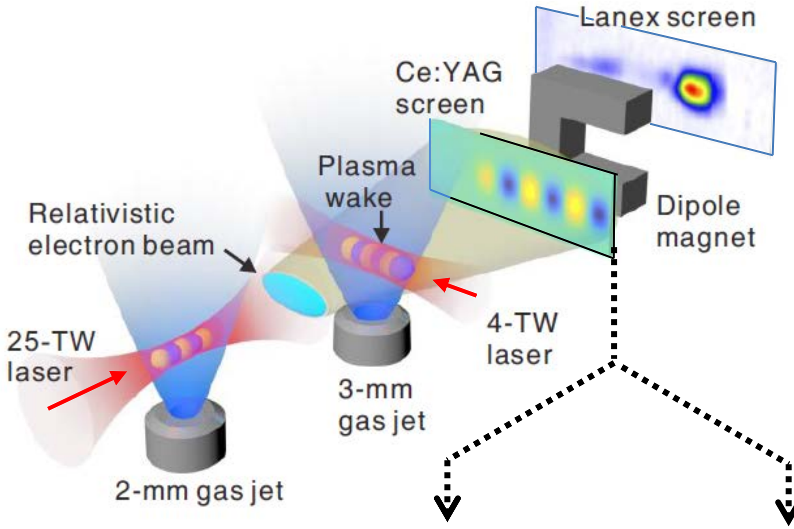
Measured average Stokes/ anti-Stokes amplitude

J. Welch, *et al.*, "Observation of SM-LWFs driven by TW CO_2 laser," in prep. for *PR-Accel. Beams* (2019).

Probing of Linear Wakes Using a Relativistic LWFA Electron Beam

W. Lu - *Tsinghua University, Beijing*

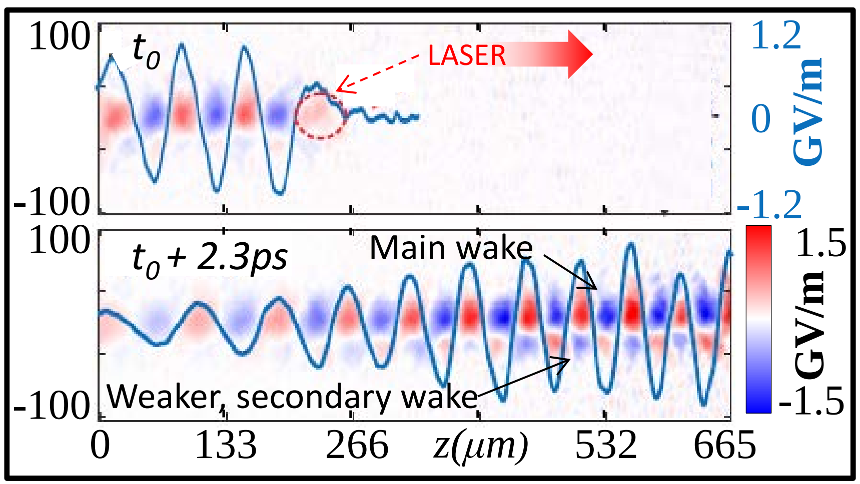
Zhang, C.J., et. al., PRL 119, 064801 (2017)
Zhang, C.J. et.al., Scientific **Reports** | 6:29485 | DOI: 10.1038/srep29485



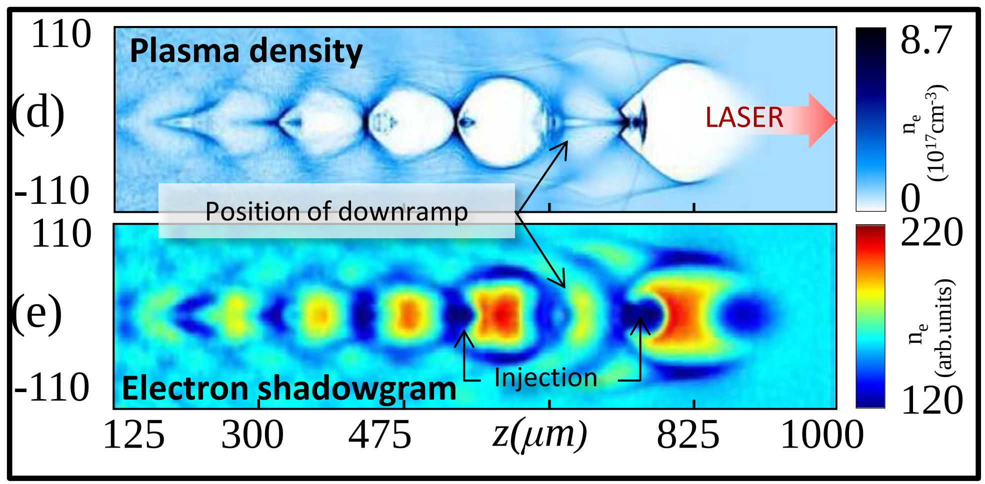
-Electron radiography is sensitive to electromagnetic fields of the plasma wave and of the accelerated charge.

-Easily scaled to low densities.

NAVID VAFAEI-NAJAFABADI
DIAGNOSTICS WG5 MONDAY 18:00



Measurement



Simulation

ATF's CO_2 LWIR Laser upgrades continue, latest configuration: *9.2 μm* with mixed isotopes in regen and amplifier

M. Polyanskiy, I. Pogorelsky , ATF-BNL

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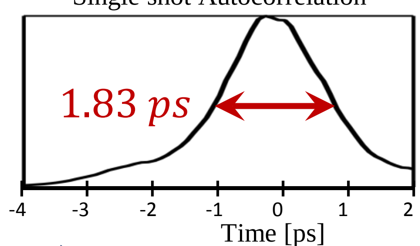
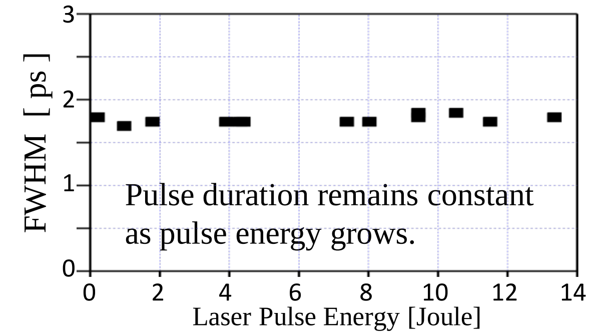
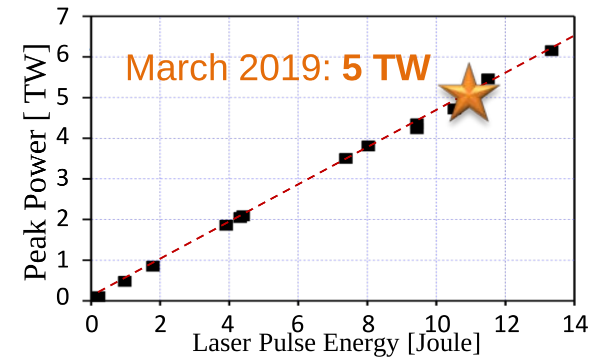
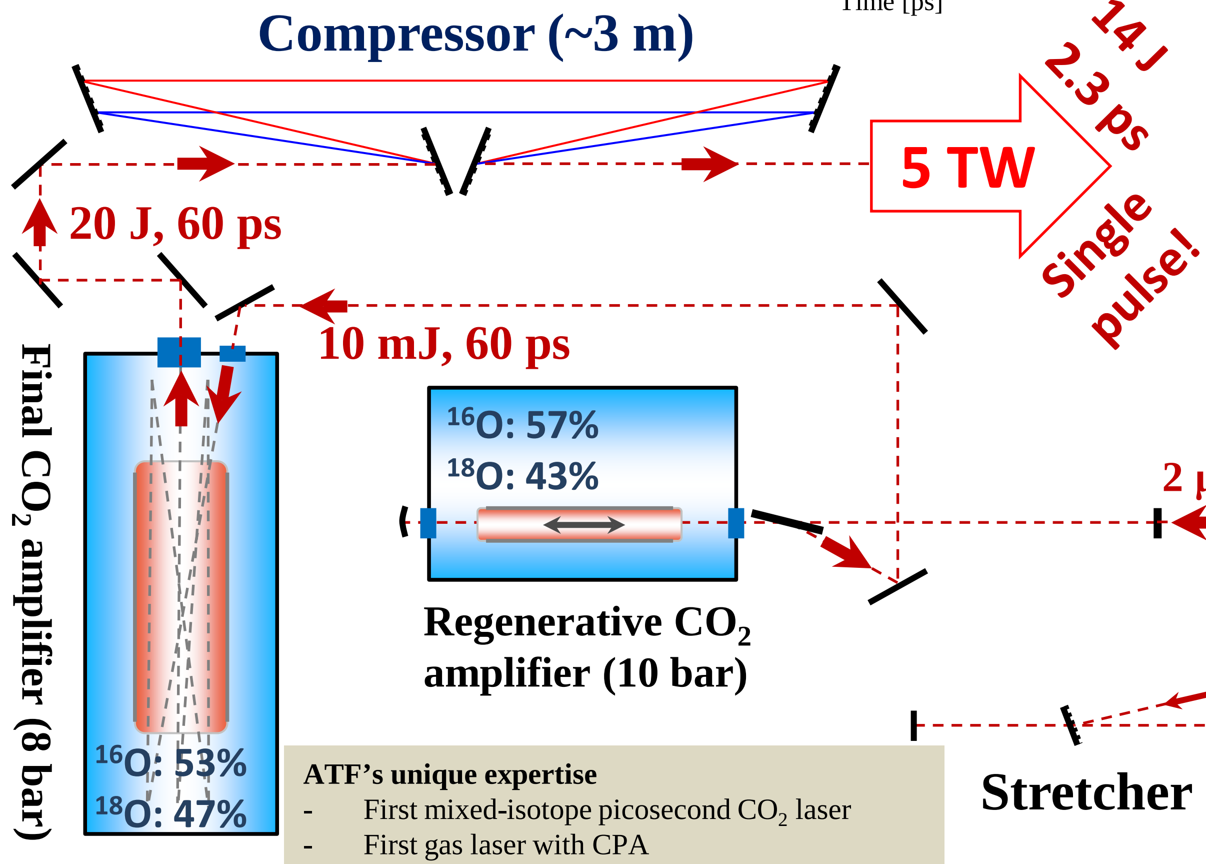
New compressor gratings

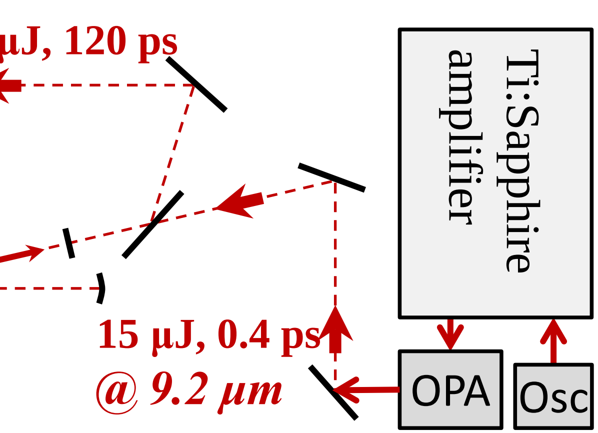
Line density:	75 → 100 lines/mm
Coating:	Al → Au
Blaze wavelength:	10.0 → 9.3 μm
Diffraction Efficiency:	84 → 92 %
Compressor Efficiency (4x):	50 → 70 %
Damage threshold:	0.5 → 2 J/cm²











ATF's unique expertise

- First mixed-isotope picosecond CO_2 laser
- First gas laser with CPA
- Solid-state seed laser

OSIRIS and SPACE simulations predict self-injection, relativistic e- production at P_{CO2} > 1 TW...

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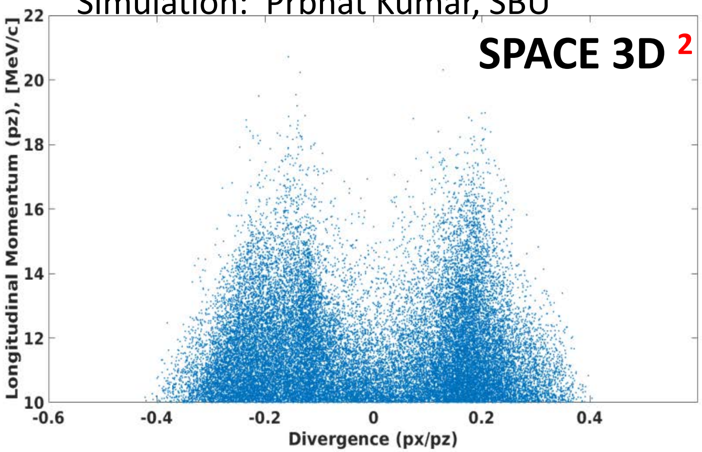
Stony Brook University

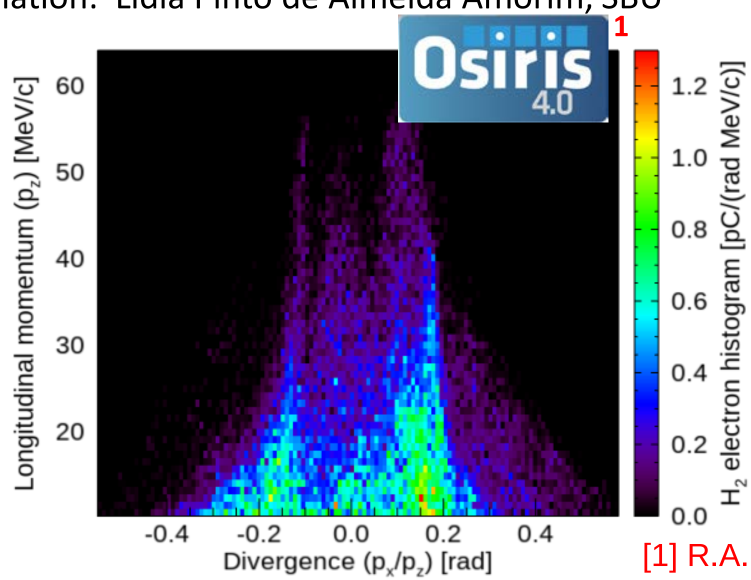
Simulation: Prbhat Kumar, SBU



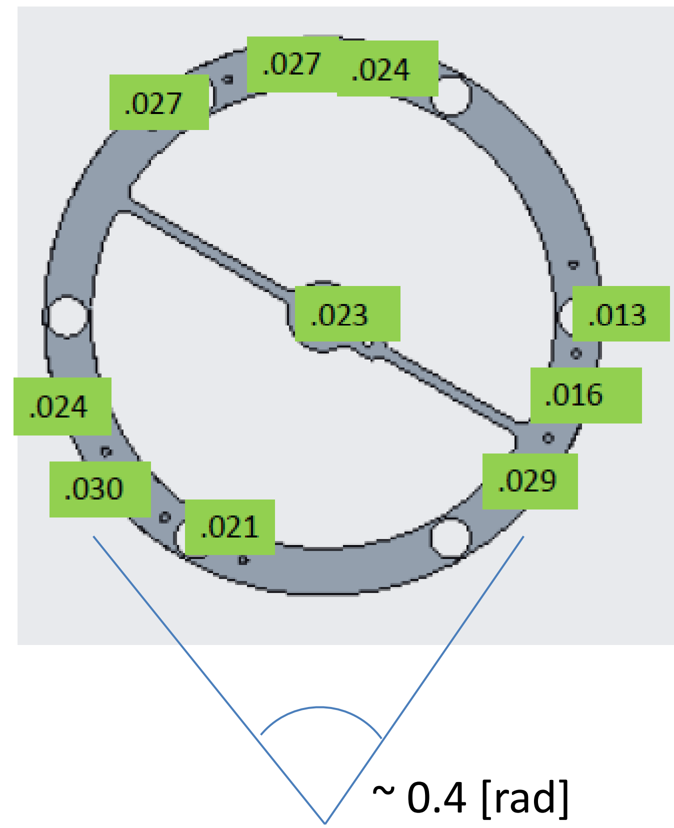
Pump parameters
w0 =20micron
2ps
4J

1.2 mm H_2 jet
ne=7.5 $10^{17}cm^{-3}$

Simulation: Lidia Pinto de Almeida Amorim, SBU



Pre-experimental safety approval test. The readings below are in Rad's, after 100 shots, behind ¾ inch steel. The angle covered by the detectors is within the predicted electron emission cone.



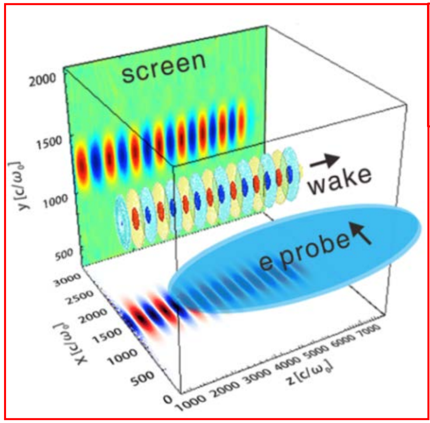
[1] R.A.Fonseca *et al.*, NCS 2331, 343 (2002)
[2] K. Yu, R. Samulyak, "SPACE code for beam-plasma interactions," *Proc. IPAC*, 728 (2015)

Summary

1) Plasma wakes produced by BNL/ATF's 0.5 TW, 10mm, 2J CO_2 laser in the self-modulated regime.
2) Wakes detected and characterized by collective Thomson scatter of a 532nm, 4ps probe.
3) Confirmed injection and acceleration of electrons to multi MeV energy with ~2TW, 2ps pump pulses.
3) **OSIRIS**[1] and **3D SPACE**[2] PIC simulations explain ne dependent trend, show key role of ionization front seeding in the self-modulation, qualitatively reproduce the complex structure of sidebands often seen in the data, and suggest origin of sum/difference frequency peaks in CTS spectra.
4) Moved experiment to new location in the linac experimental hall. System has gone though most validations and approvals, allowing to shortly begin radiographic probing of wake fields.

[1] R.A.Fonseca *et al.*, NCS 2331, 343 (2002)
[2] K. Yu, R. Samulyak, "SPACE code for beam-plasma interactions," *Proc. IPAC*, 728 (2015)

Future Plans



1) probe wake's internal fields transversely with sychronized, few-fs e-bunches from the ATF linac[3], and longitudinal optical probe experiments.
2) Characterization of accelerated electrons: OSIRIS and SPACE simulations predict self-injection, relativistic e- production at P_{CO2} > 1 TW...
3) Addition of newer optical probing techniques, such as Frequency Domain Holography (FDH)[4], Multiple Object plain Imaging (MOP)[5], Faraday rotation for magnetic field measurement, et al. Characterize wake structure and evolution in single shot.
4) Develop on shot diagnostics for the CO2 laser beam input and output parameters. On shot profile, spectrum, duration etc.
5) Pave way for bubble regime. Reachable within the next 2-3 years.

[3] Zhang, *Sci. Rpts*. **6**, 29485 (2016)
[3] Zhang, *PRL* **119**, 064801 (2017)

[4] Matlis *et al.*, *Opt. Lett*. **38**, 5157 (2013) [5] Li *et al.*, *Opt. Lett*. **38**, 5157 (2013)

LPAW 2019, DIAGNOSTICS WG5 MONDAY 18:00
Navid Vafaei-Najafabadi