Transverse electron probing of interactions of long CO_2 laser pulse with plasma at ATF

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Plasma
Acceleration
Group

Stony Brook
University

ATF **AE-71** Collaboration

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Acknowledging funding from DOE Grant No. 215125

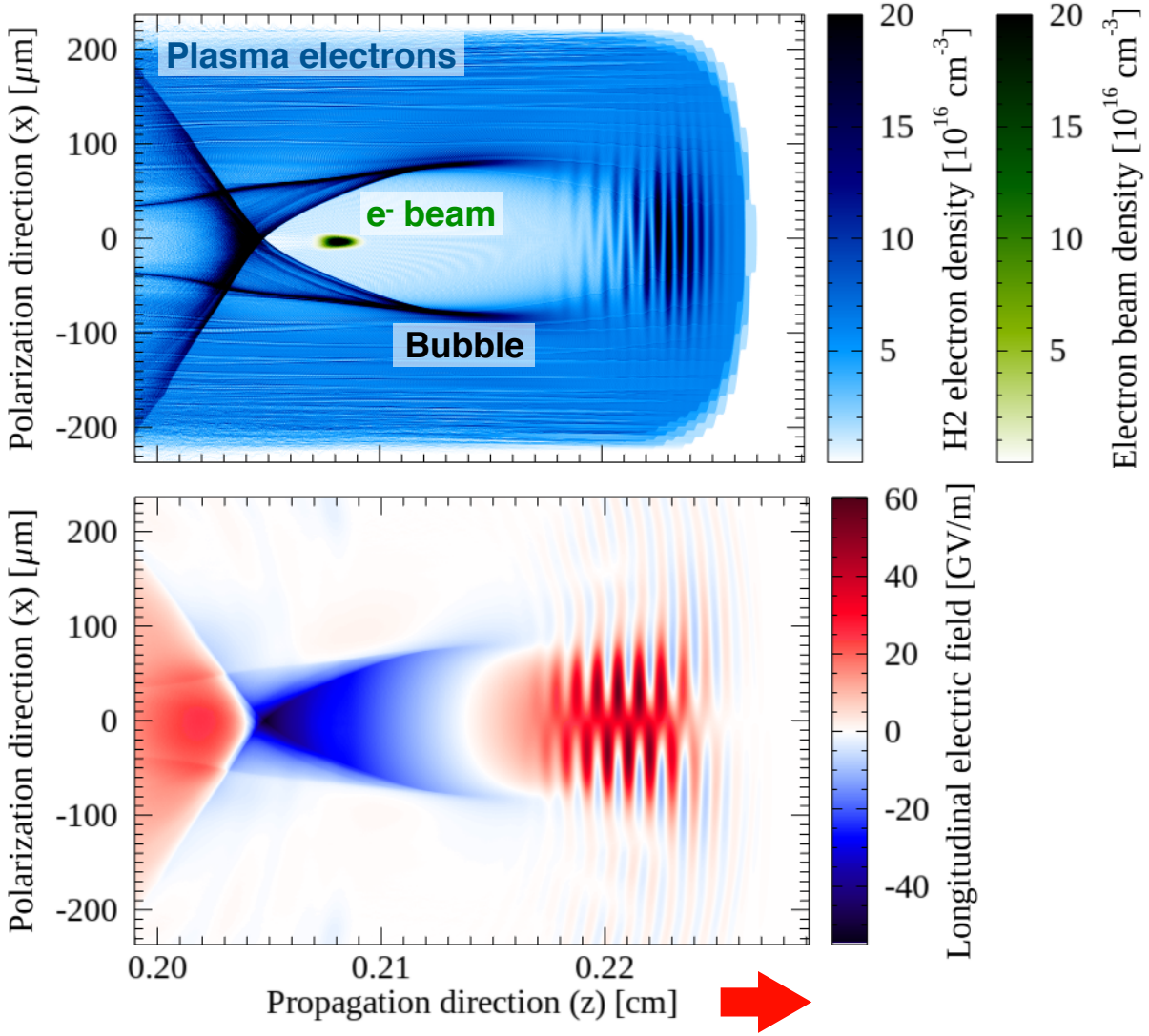
CORI@NERSC facility, operated under Contract No. DE-AC02-05CH11231

Bubbles driven by CO_2 laser (~10μm λ_0) are ≈170μm long

Unique ATF's CO_2 laser system has λ_0≈10 μm and TW-class pulses

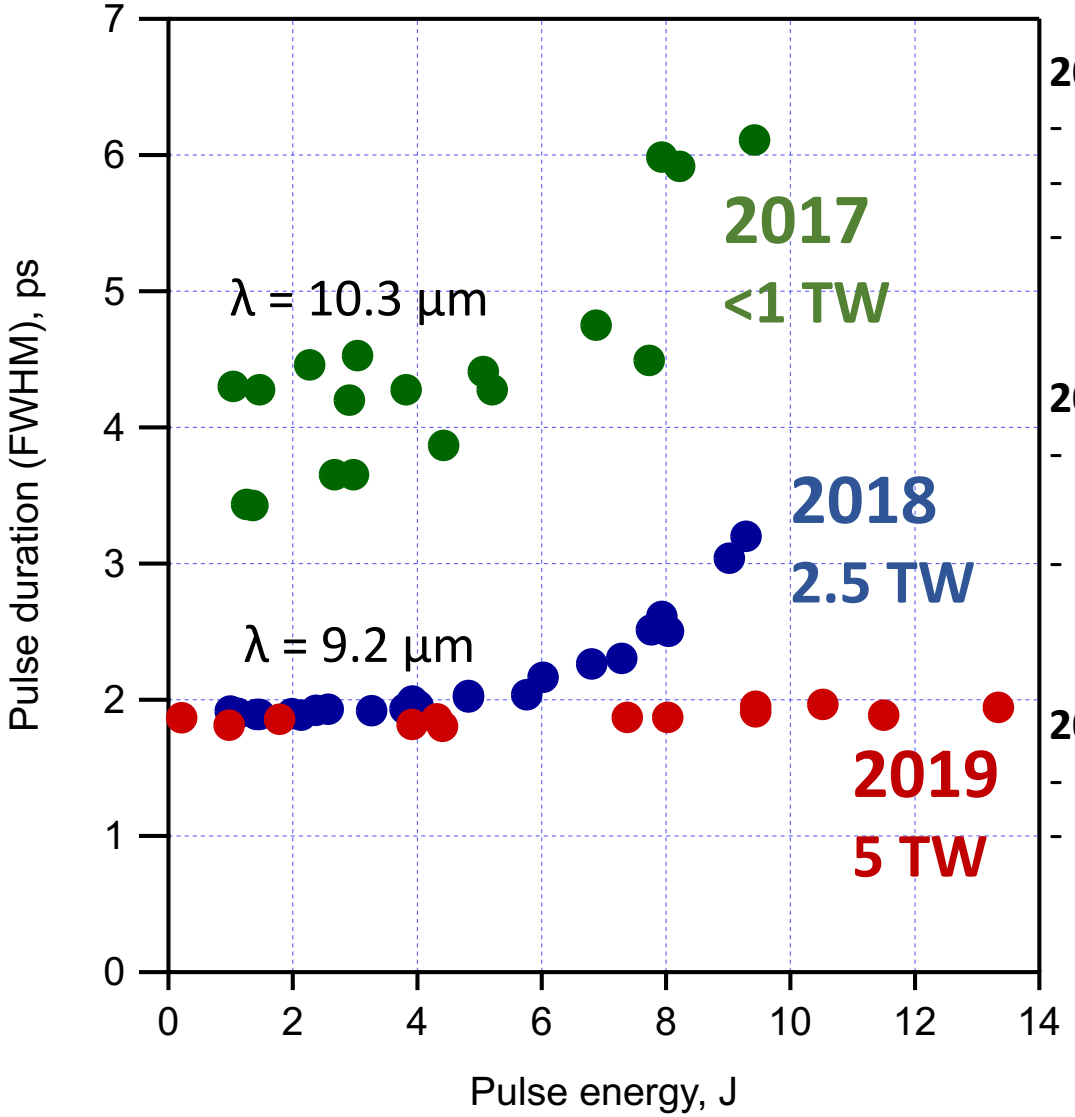
If compressed to ≈200 fs, it will drive plasma wakefields with bubbles as long as 170μm

Enabling external injection of ATF's e^- beam into accelerating phase with ≈25 GeV/m



Towards Sub-ps CO_2 Pulses at ATF

Recent CPA CO_2 laser development

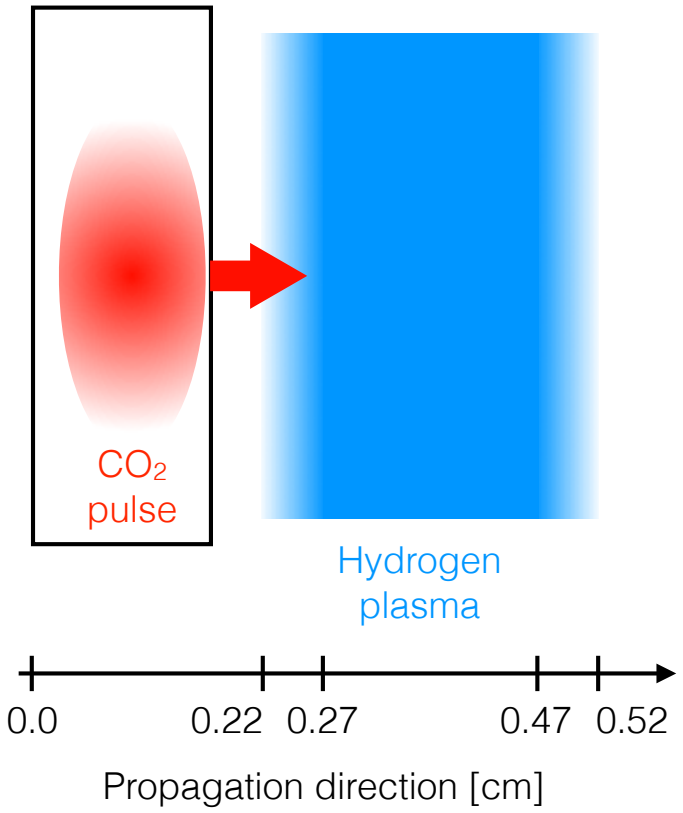


2017
- mixed-isotope regen
- 66 % of energy in 1st pulse
- compressor efficiency 50 %

2018
- mixed-isotope regen and final amplifier
- 87 % of energy in 1st pulse

2019
- 2× chirp (denser gratings)
- compressor efficiency 70 %

Currently, ATF CO_2 laser encompasses ≈44 plasma wavelengths



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

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

dt = 0.03

Simulation done in 2D geometry

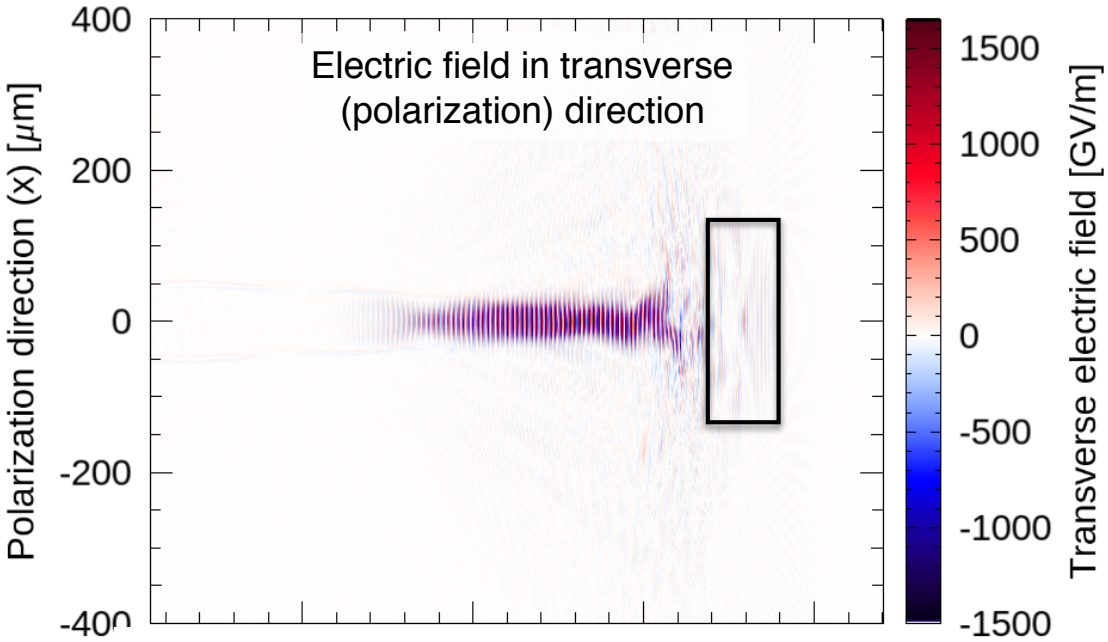
With ADK model of ionization with mobile ions

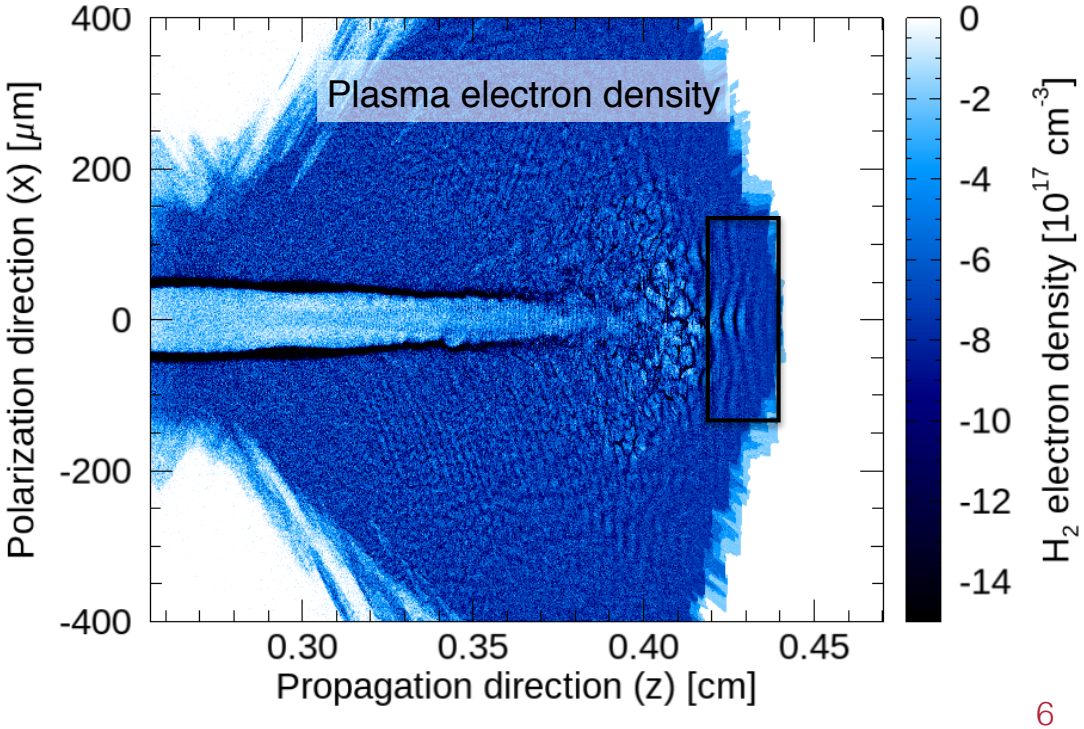
Moving window (0.21cm long / 0.36cm wide)

Longitudinally:
9400 cells
(60 per λ_0)

Transversely:
5500 cells
(30 per W_0)

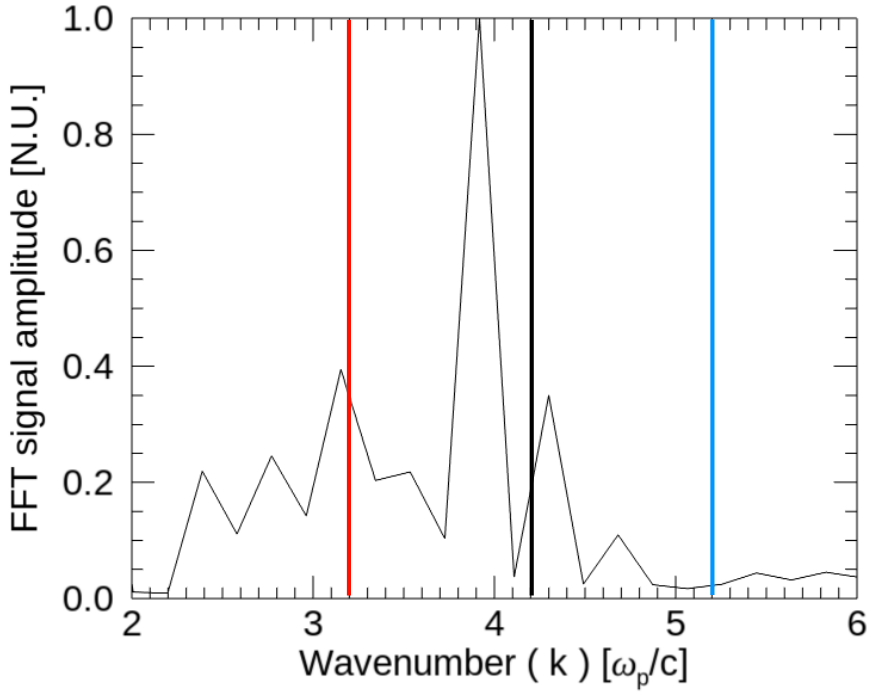
Self-modulation stokes shift appears in field spectra



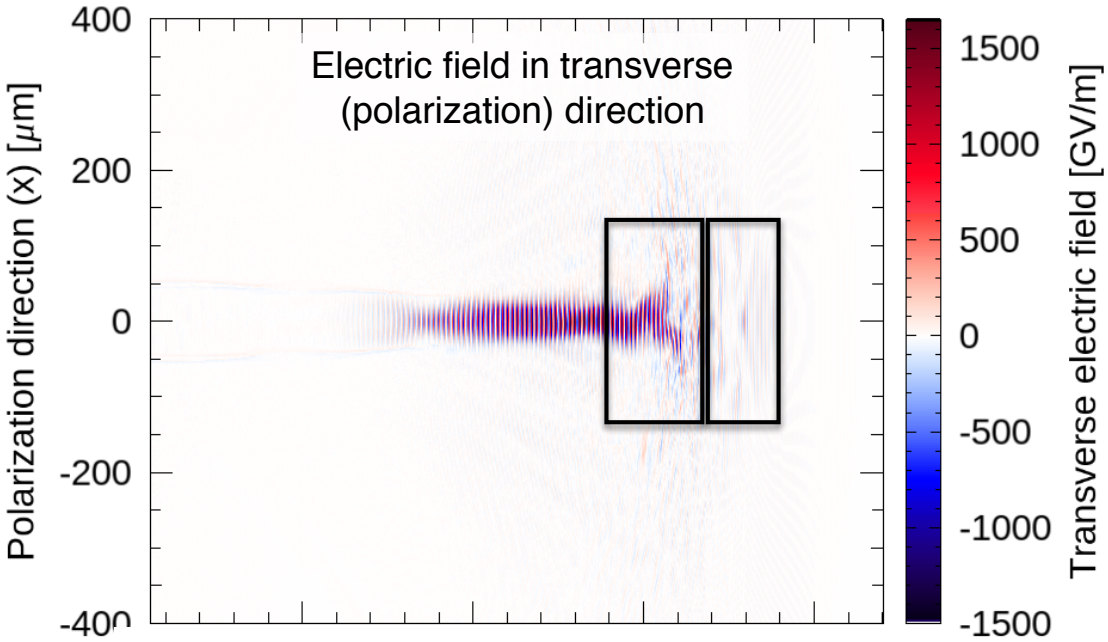


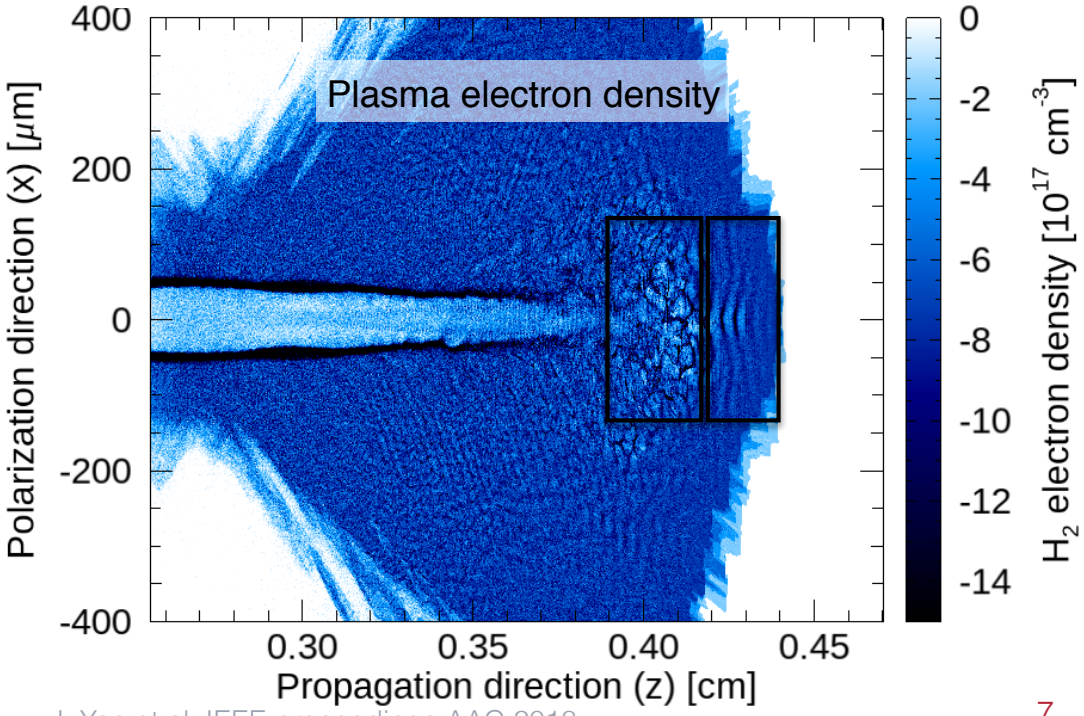
(Spectra of the field in polarization direction taken for each transverse slice, r_i, and then averaged over r_i, within black box region)

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



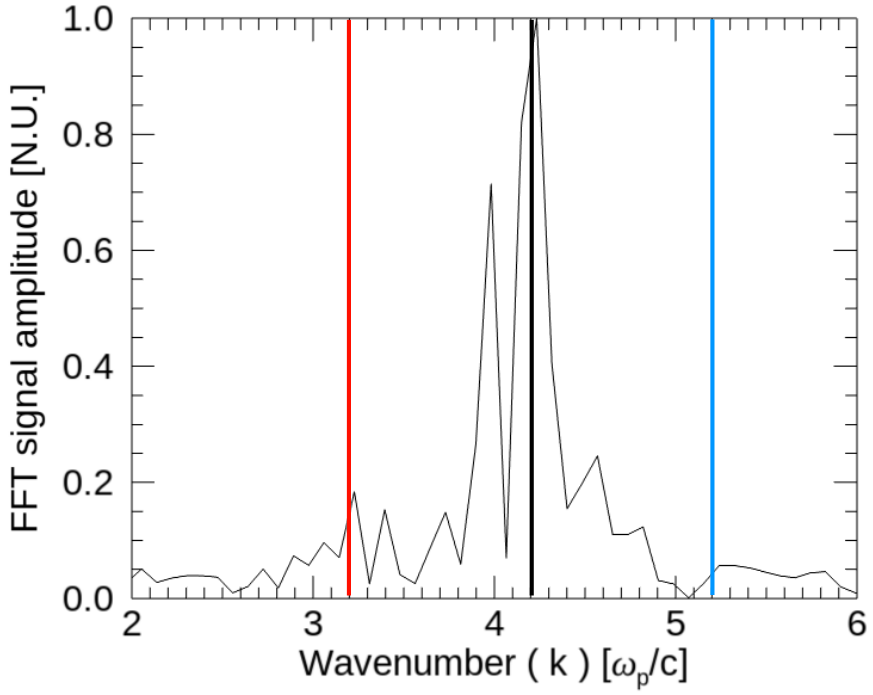
Self-modulation is followed by non-linear “hosing-like” phenomena



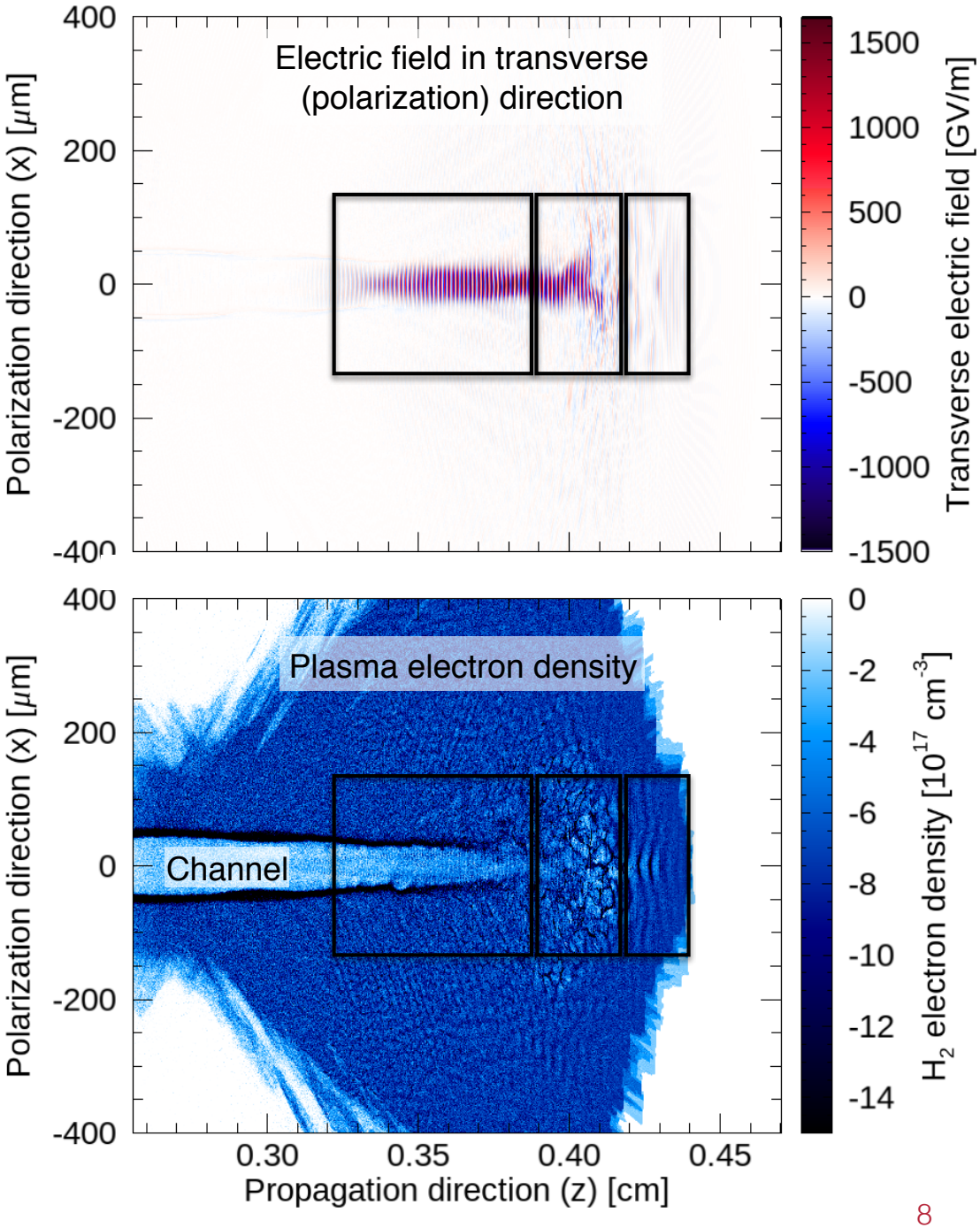


The “hosing-like” phenomena contributed to peaks between fundamental and stokes/ anti-stokes shifts (clearer at end of run)

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

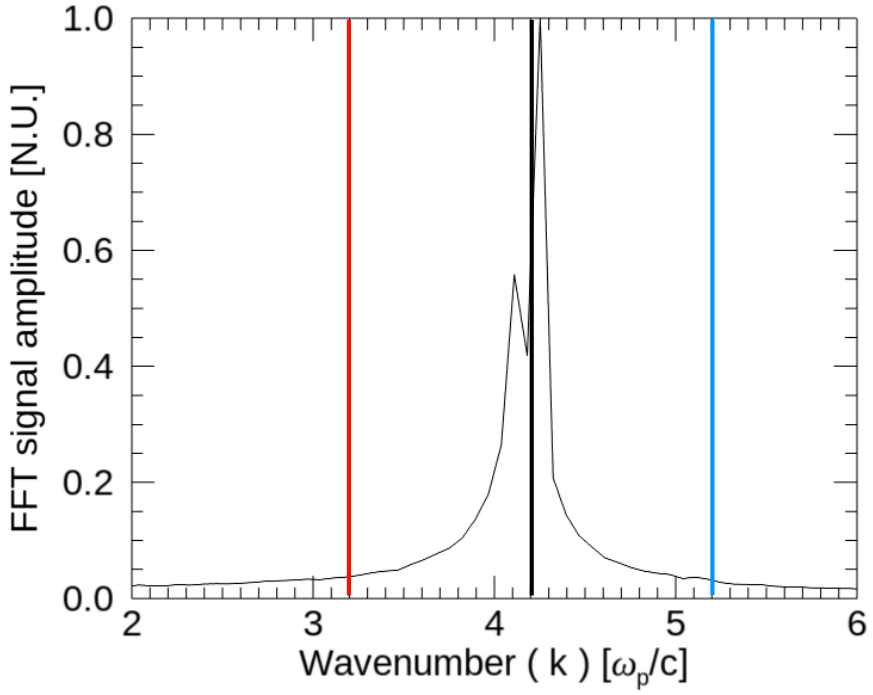


Back of laser is guided in plasma depleted channel

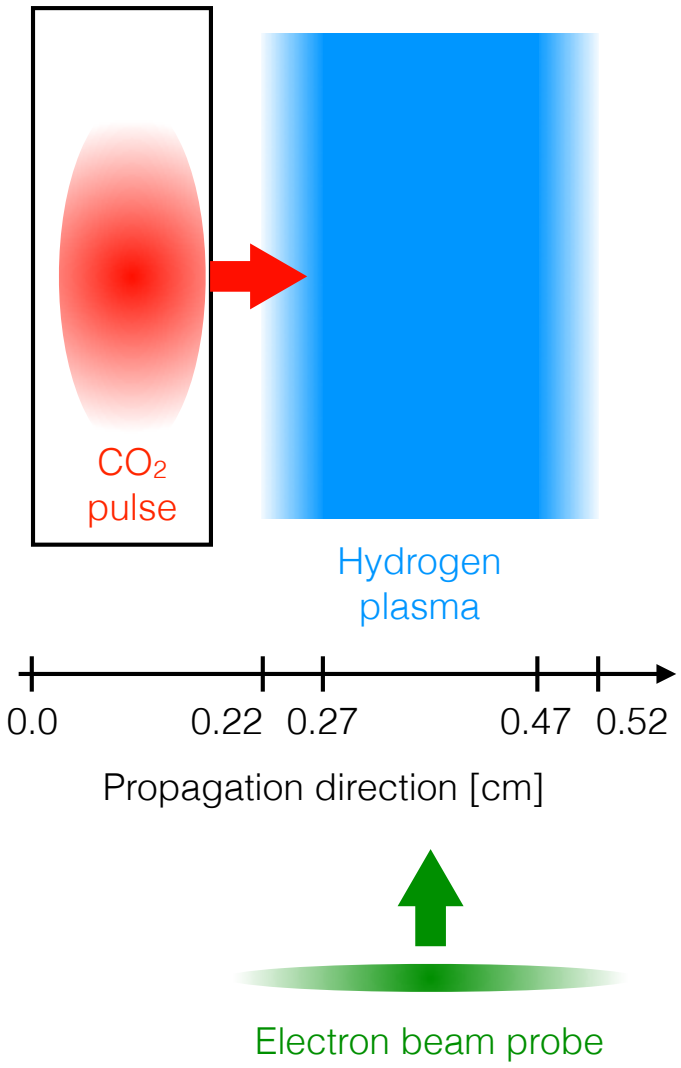


Inside the plasma channel depleted of ions and e-s the laser wavenumber shifts are small

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



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	7.5×10^{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)

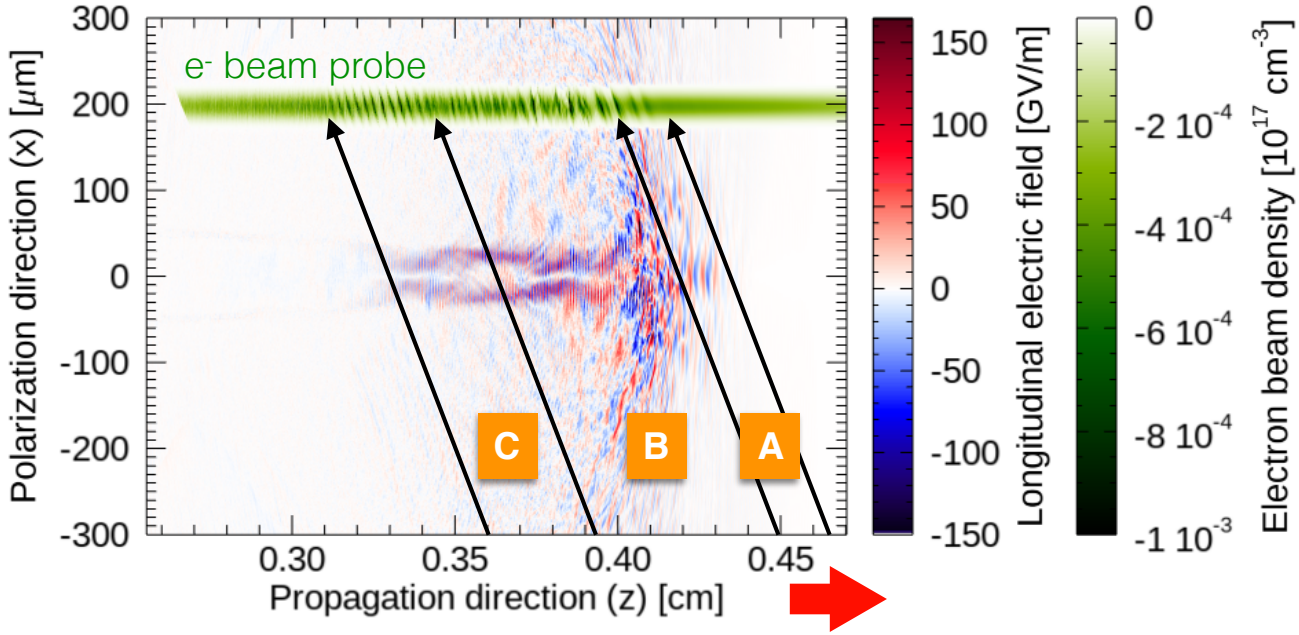
Transversely:
5500 cells
(30 per W_0)

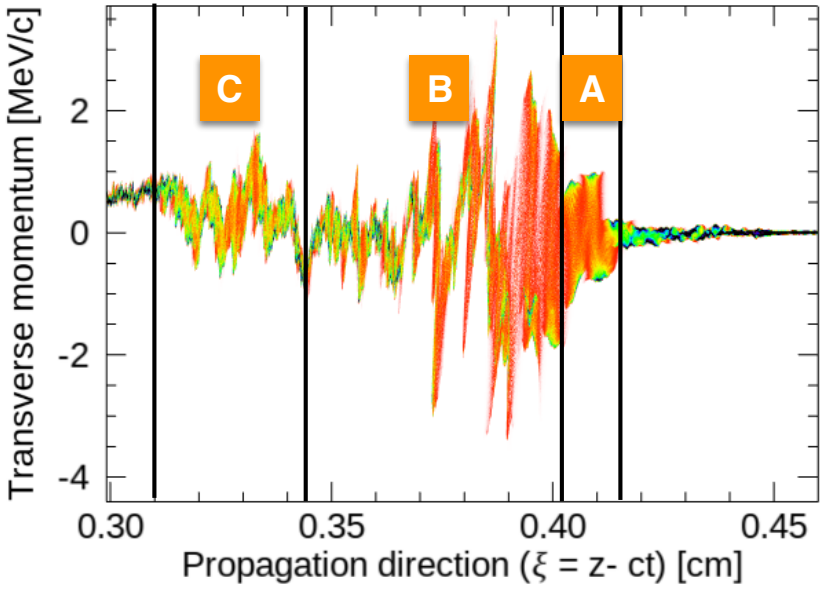
e- beam modulations are characteristic of each interaction regime

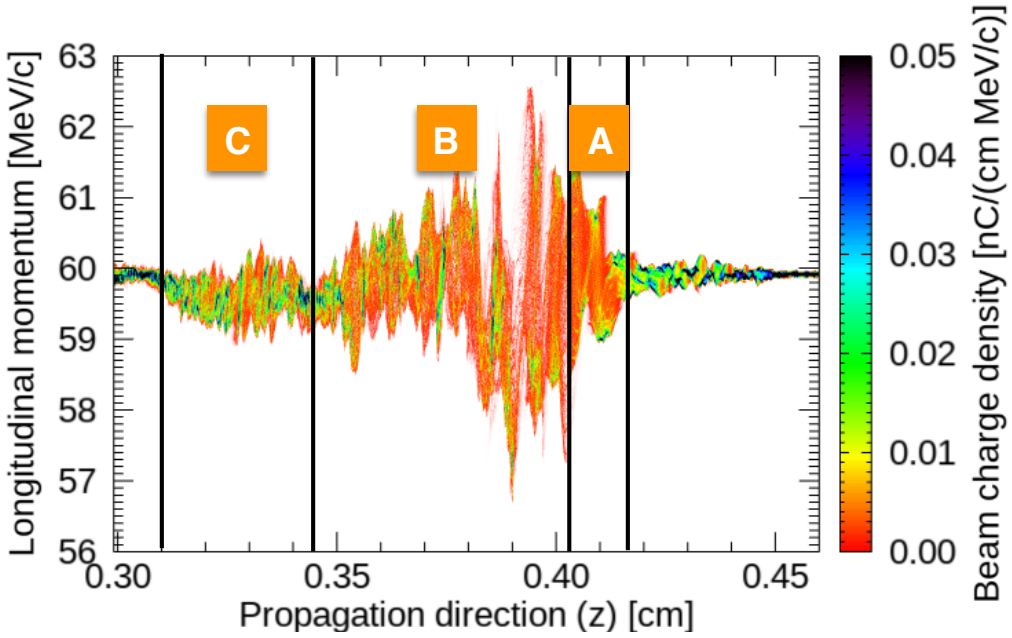
A In region of laser self-modulation e-beam shows structures at ≈ λ_p

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)

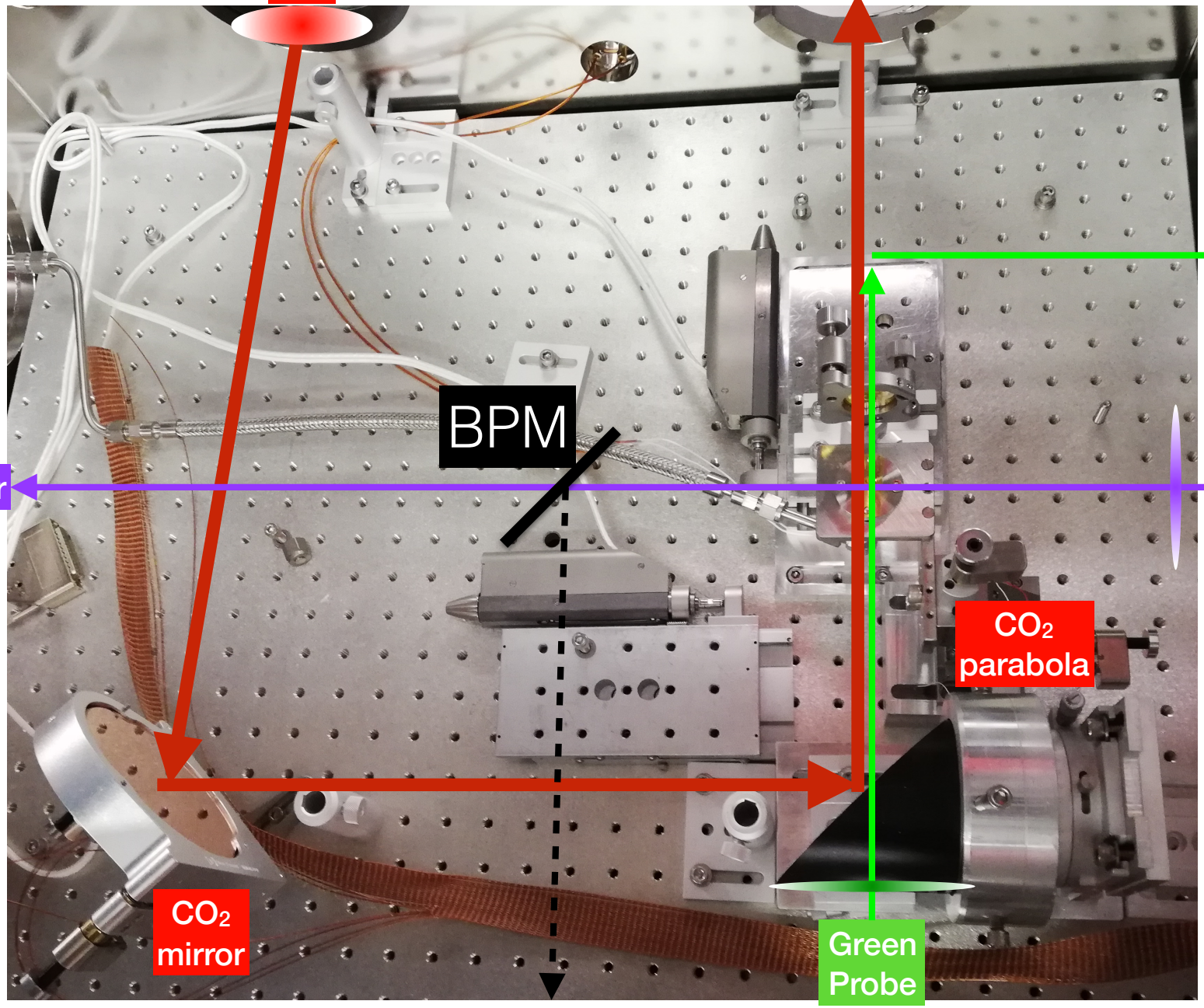
C Probe beam is modulated at ≈ λ_0







Experimental Layout



Status of the Experimental Preparation

Primary systems enabling the experiment have been completed:

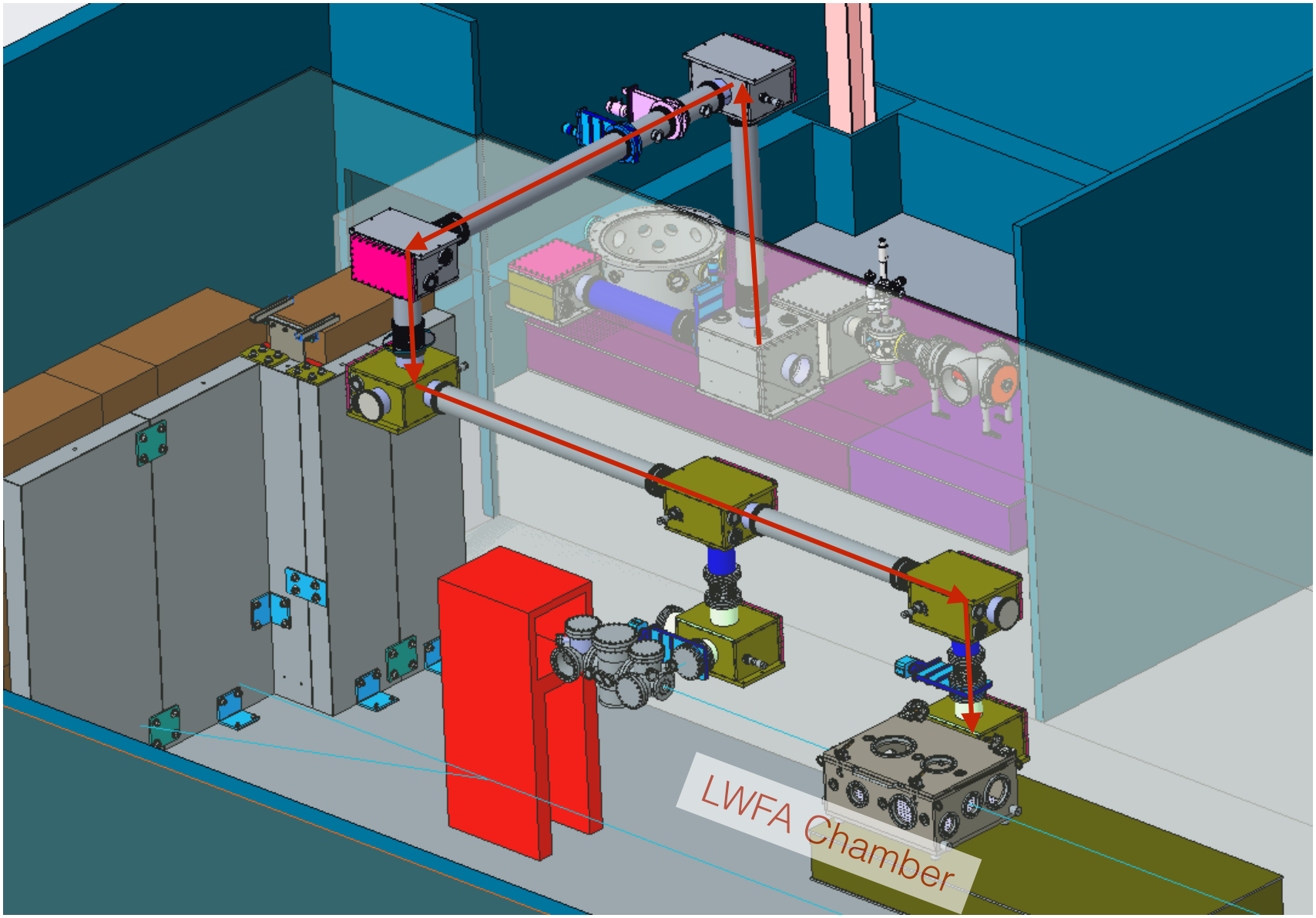
- Gas delivery system — Complete and Tested
- Differential Pumping — Complete and Tested
- CO2 Laser Delivery — Complete
- Radiation Safety Study of the Experiment — Complete

Systems required for data acquisition are currently being tested and set up:

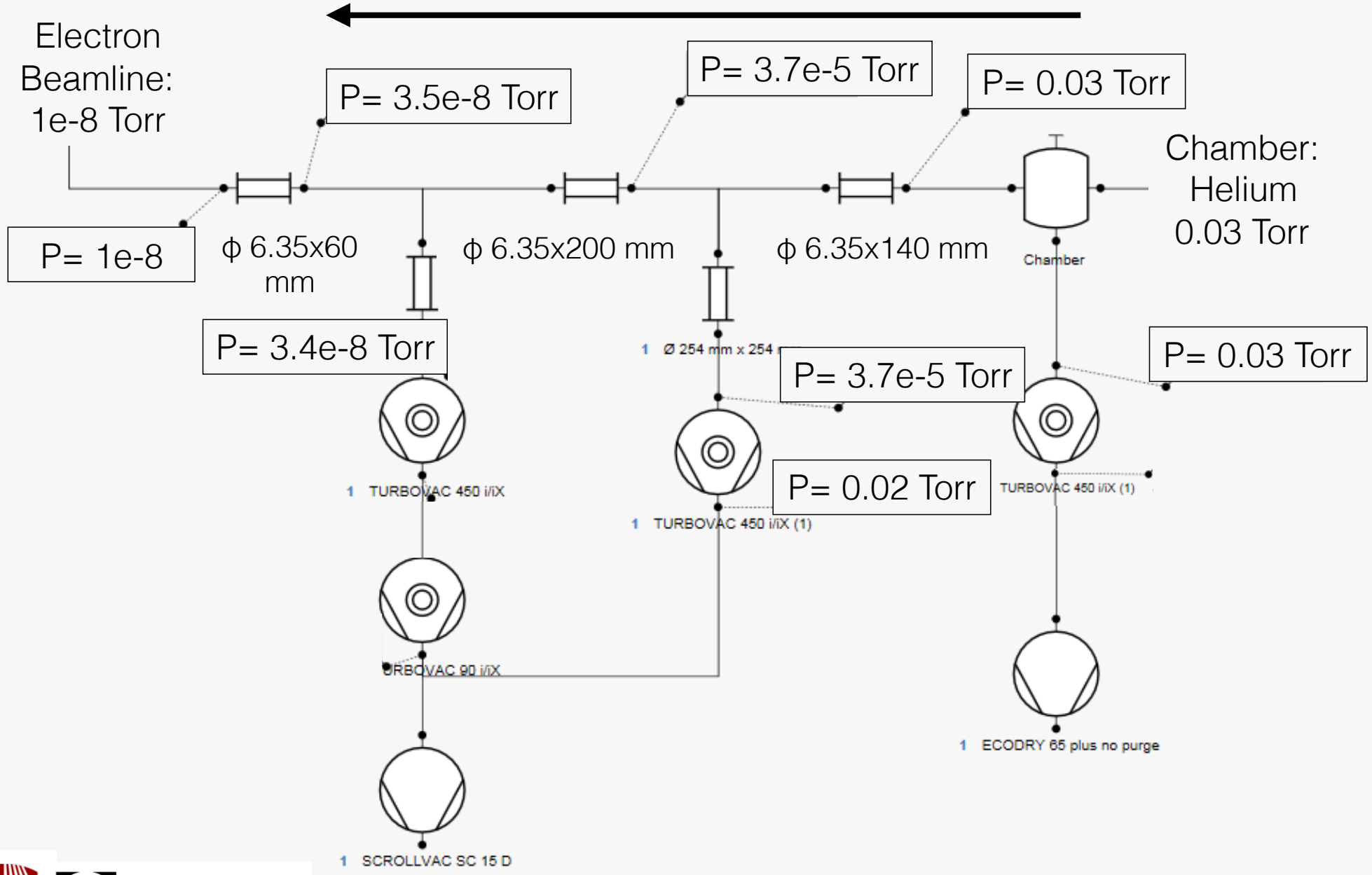
- BPM Systems and Imaging —To be tested
- YAG Transport Path — To be completed

We are almost there!

Enabling Laser e-beam Integration: Laser Transport

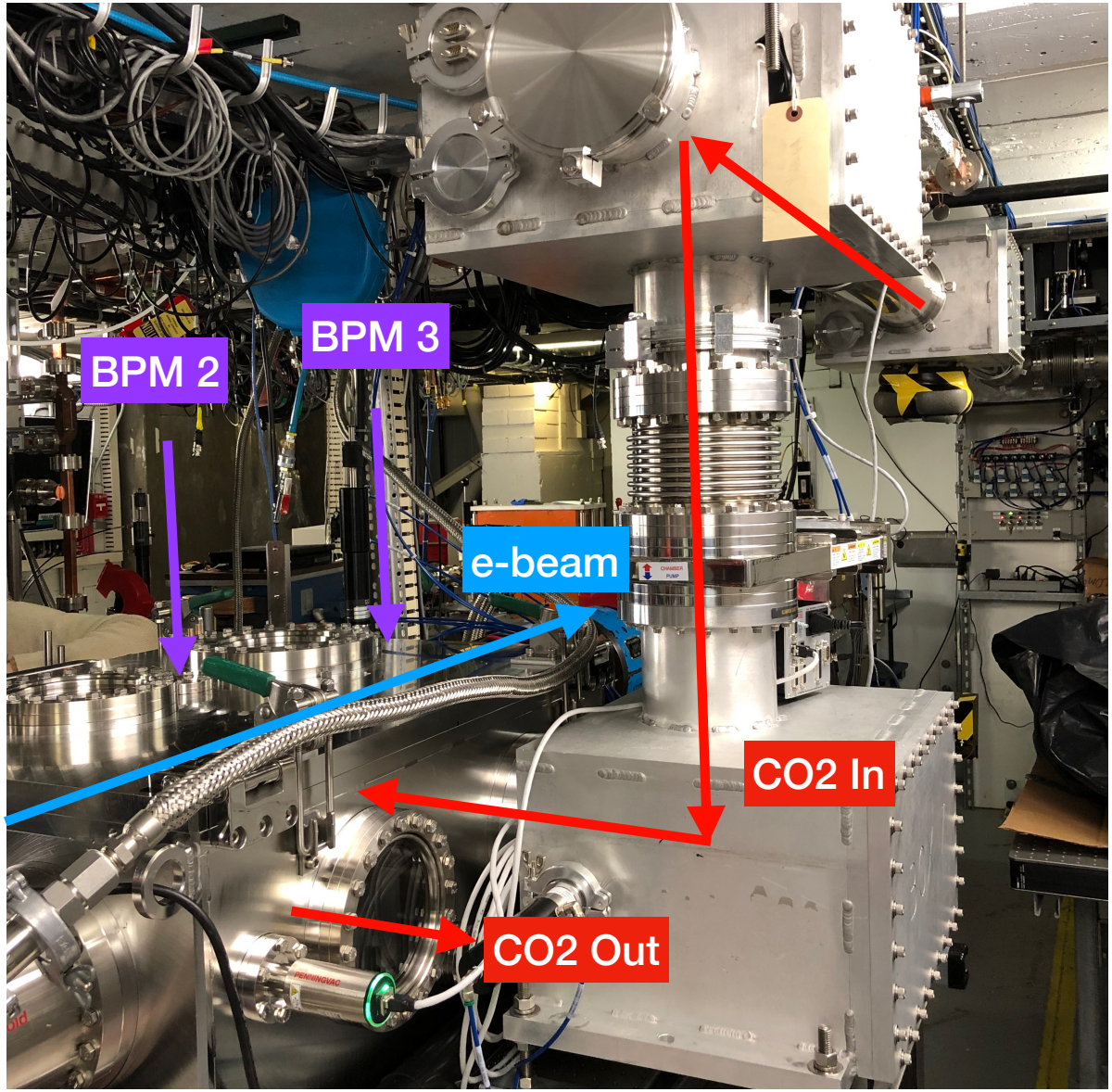


Enabling Laser e-beam Integration: Differential Pumping

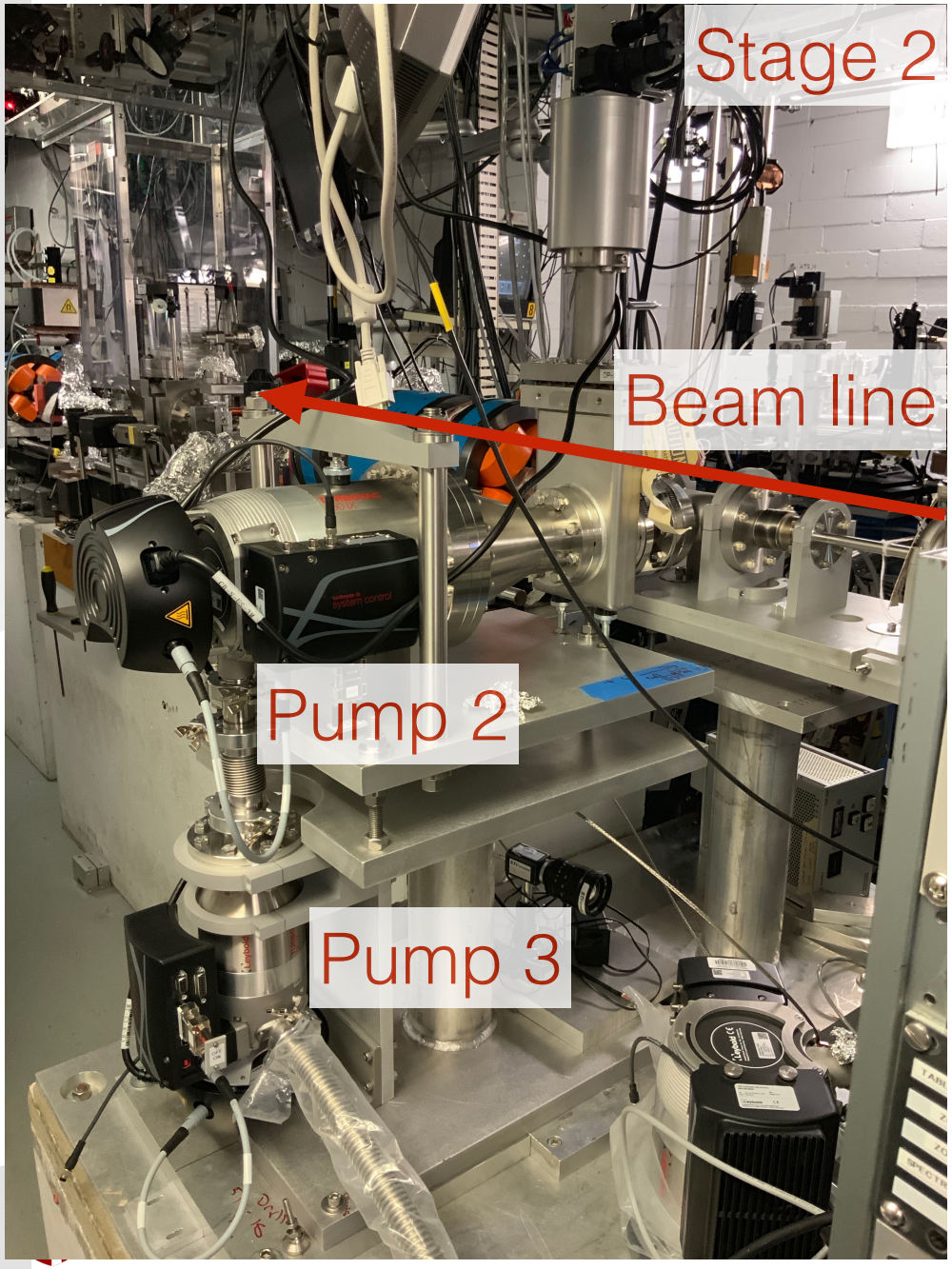


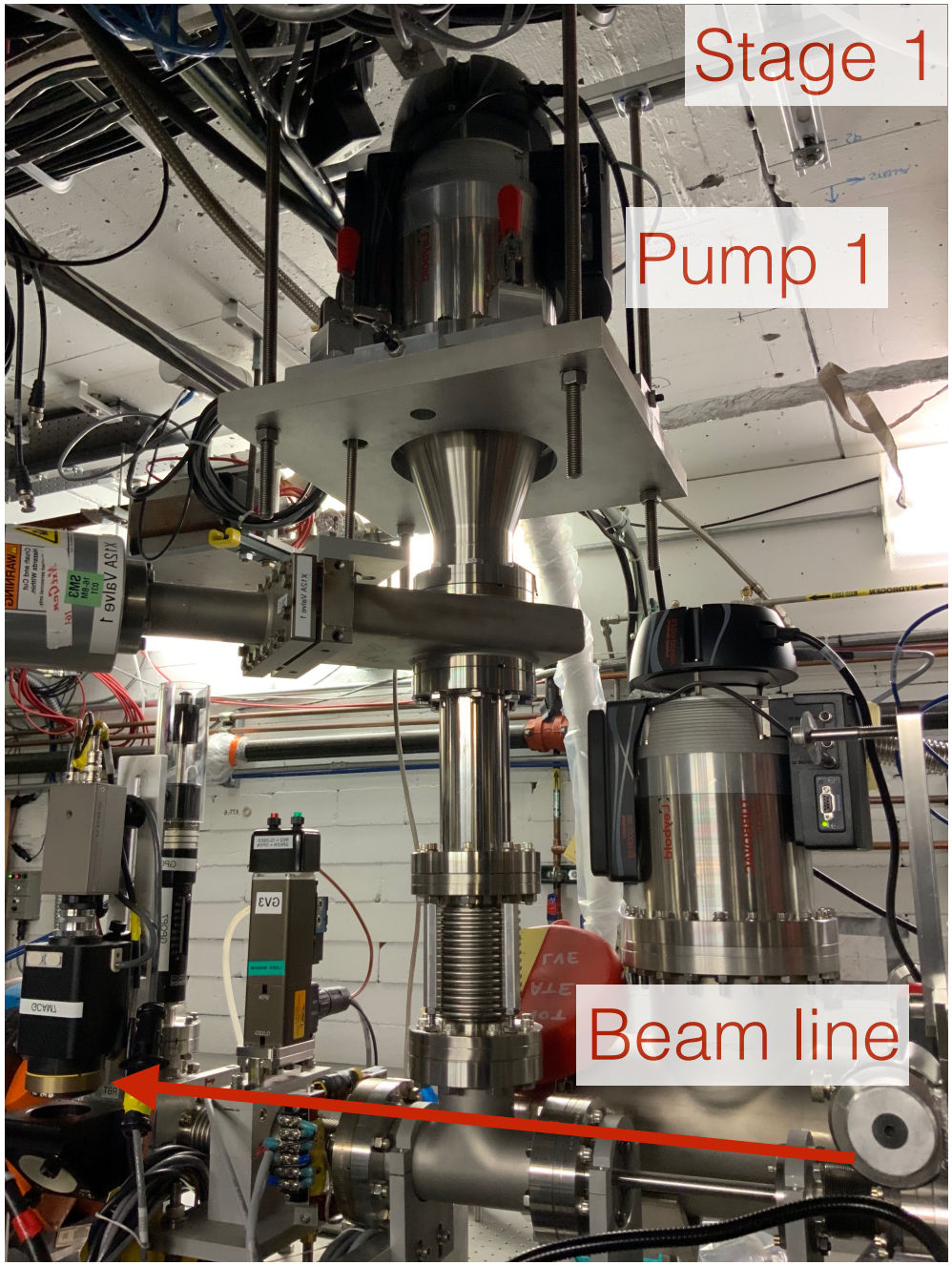
Simulation results courtesy of Leybold

LWFA Experimental Chamber

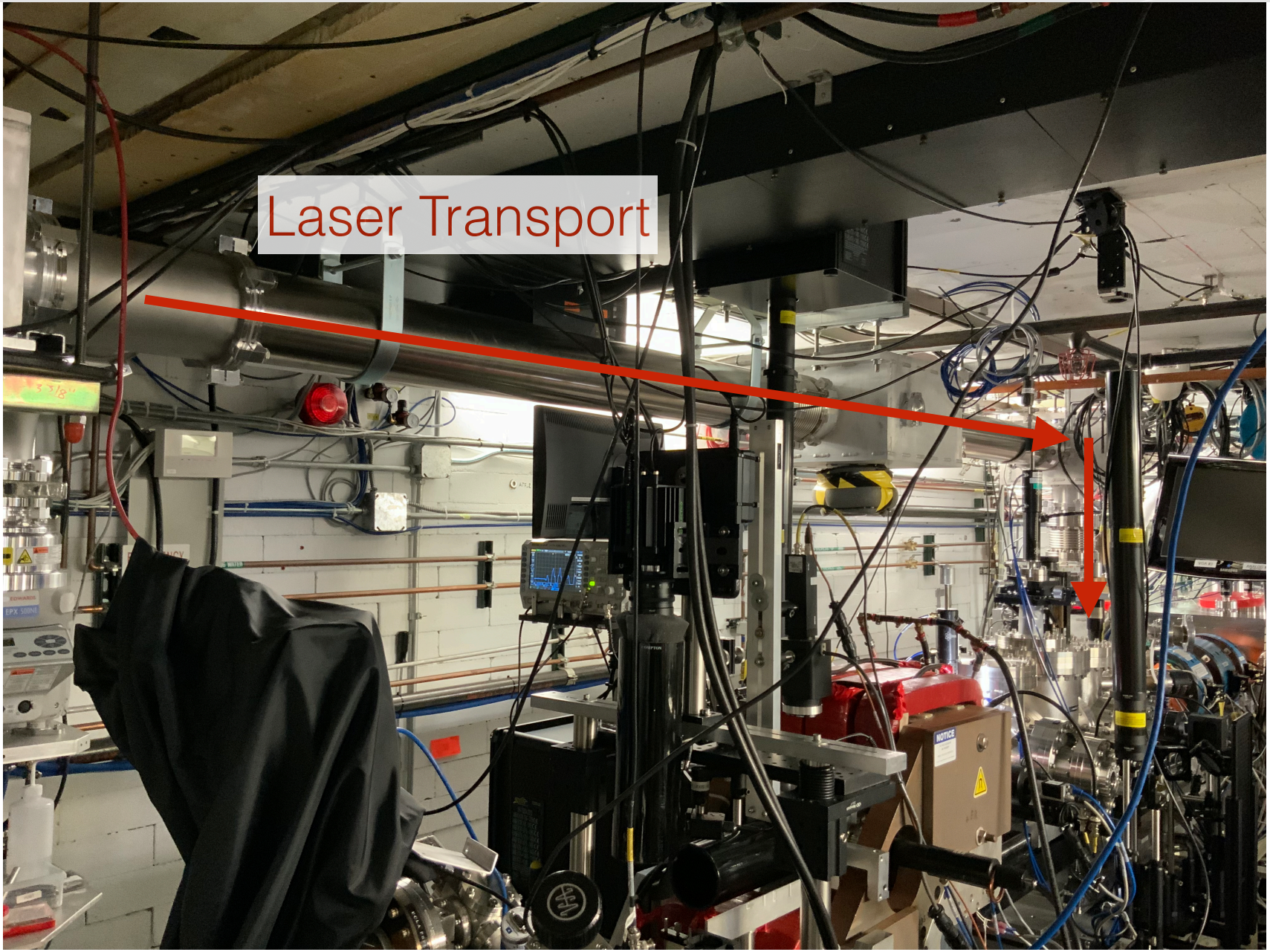


Differential Pumping Stages





Experimental Hall

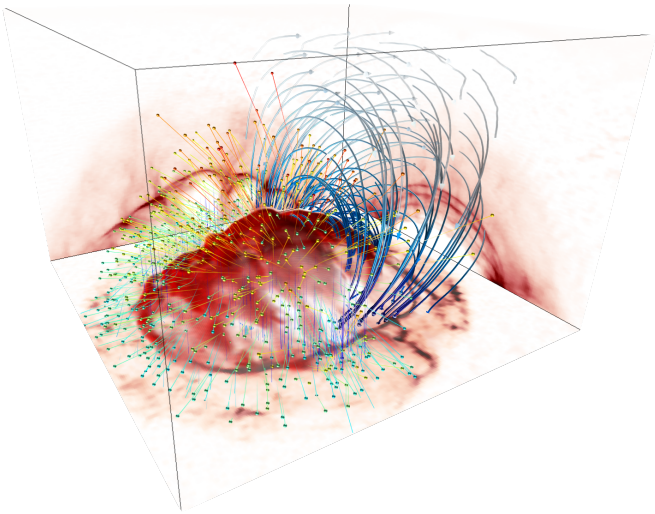


Current ATF parameters were explored with OSIRIS **CORI**@NERSC

Osiris 4.0

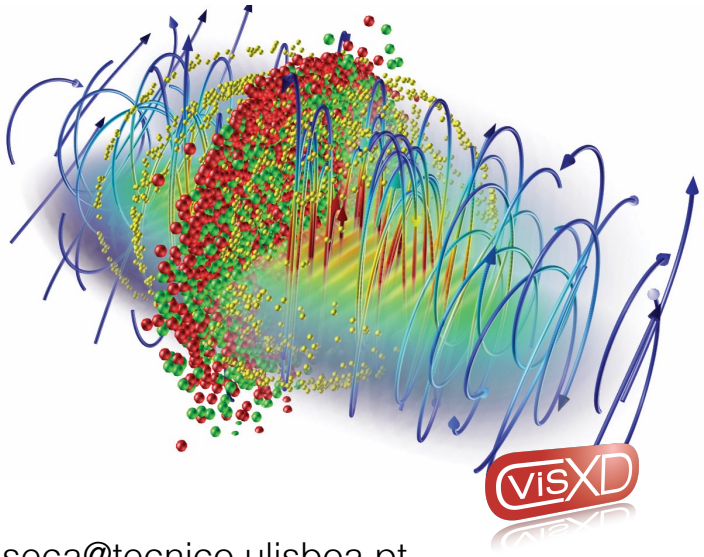
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



TÉCNICO LISBOA

UCLA



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Adam Tableman: tableman@physics.ucla.edu

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

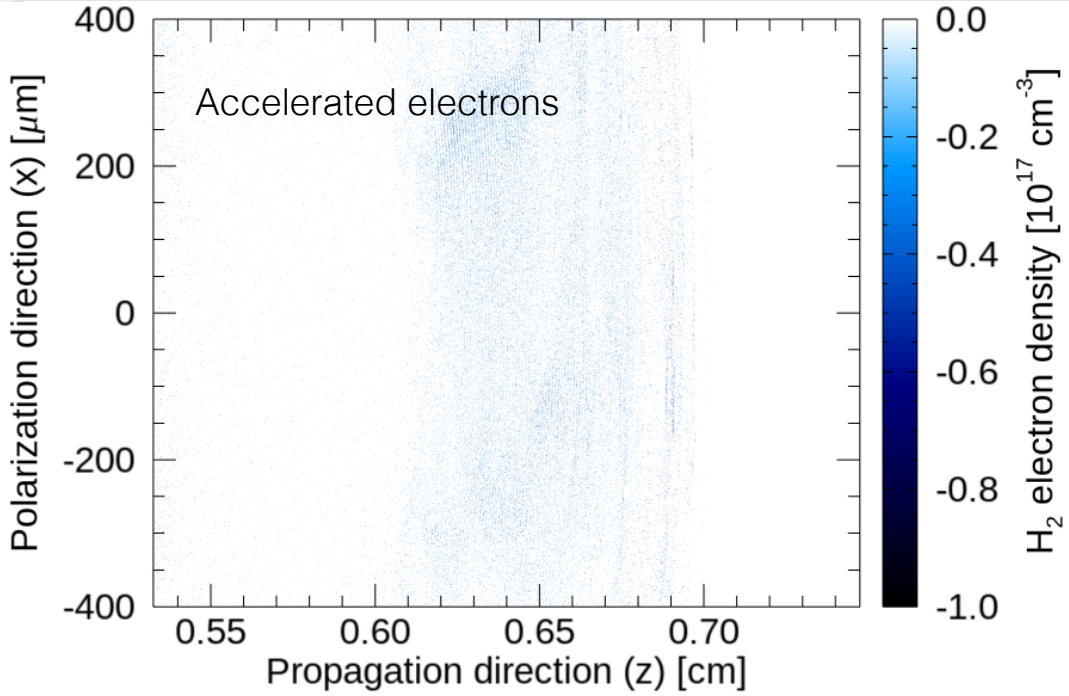
code features

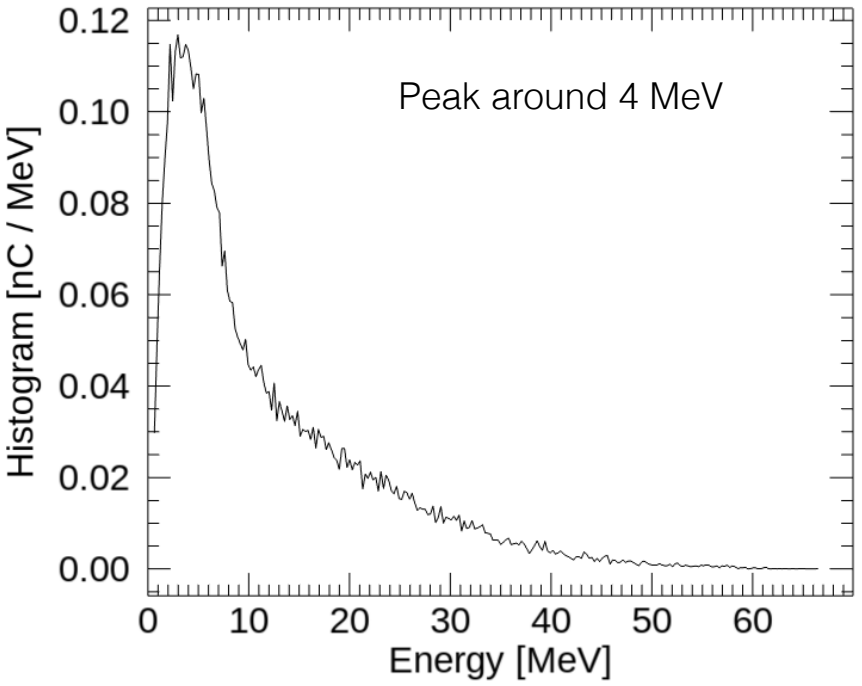
- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

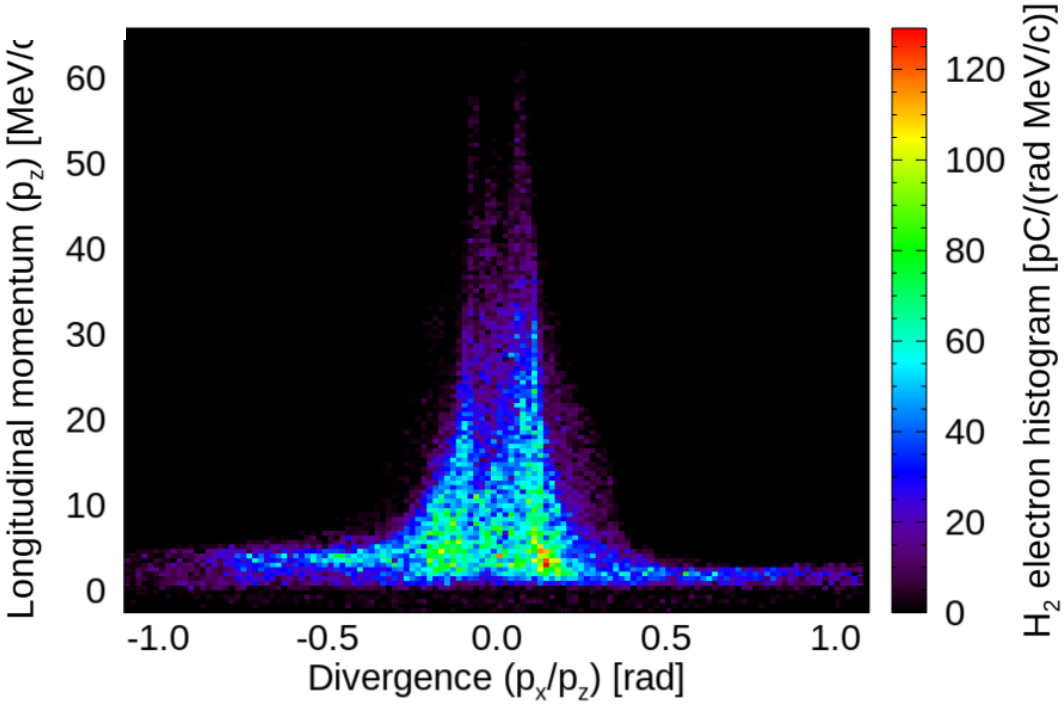
Thank you!

Extra slides

Self-trapped plasma electrons reach 60 MeV



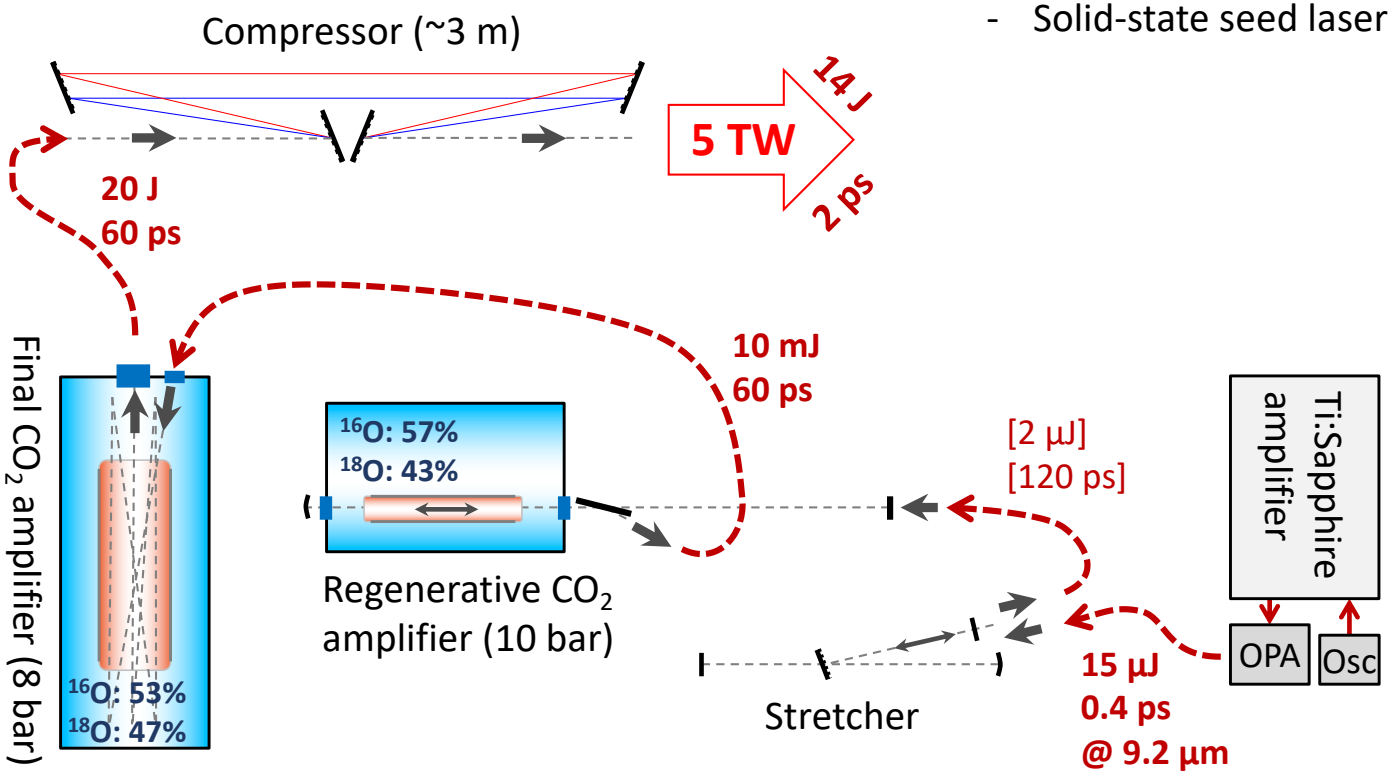




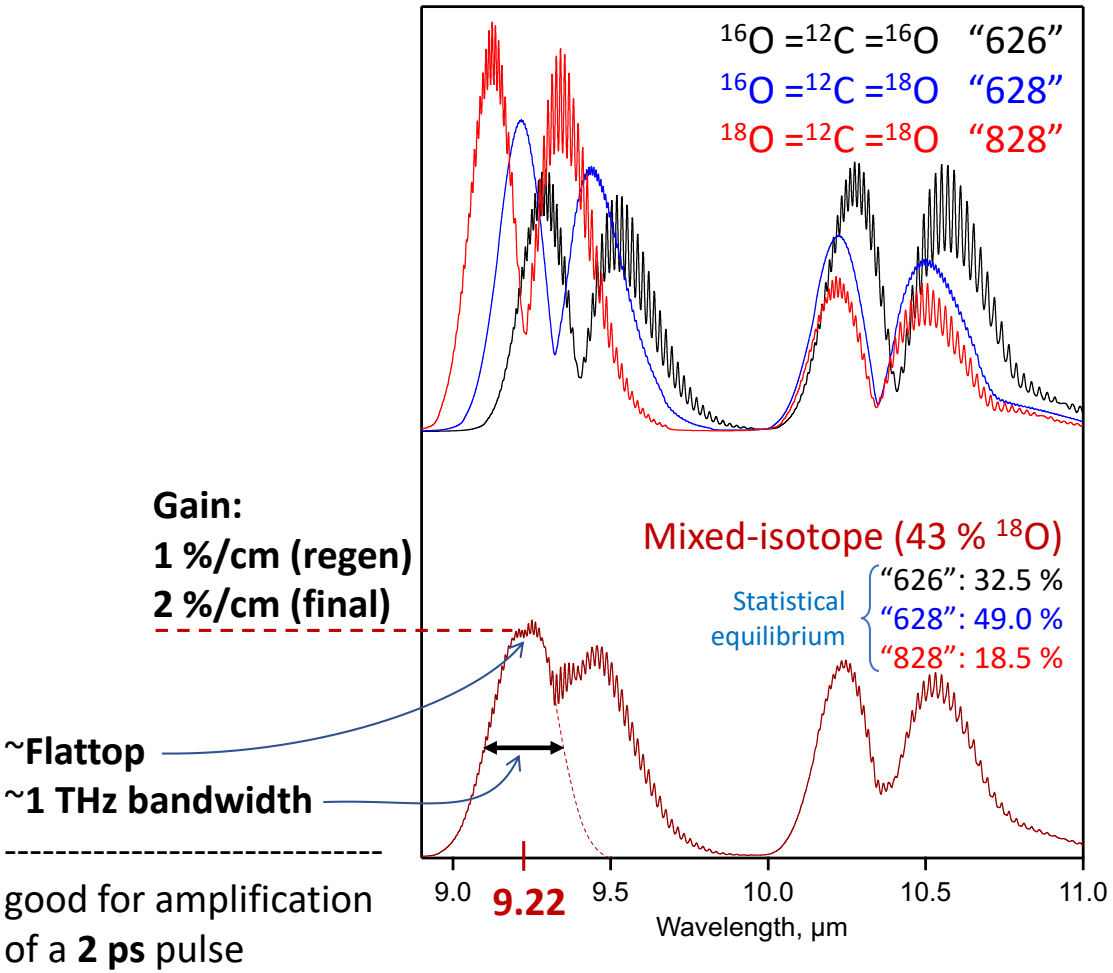
ATF's **5 TW** Long-Wave IR (**9.2 µm**) Laser

ATF's know-how

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



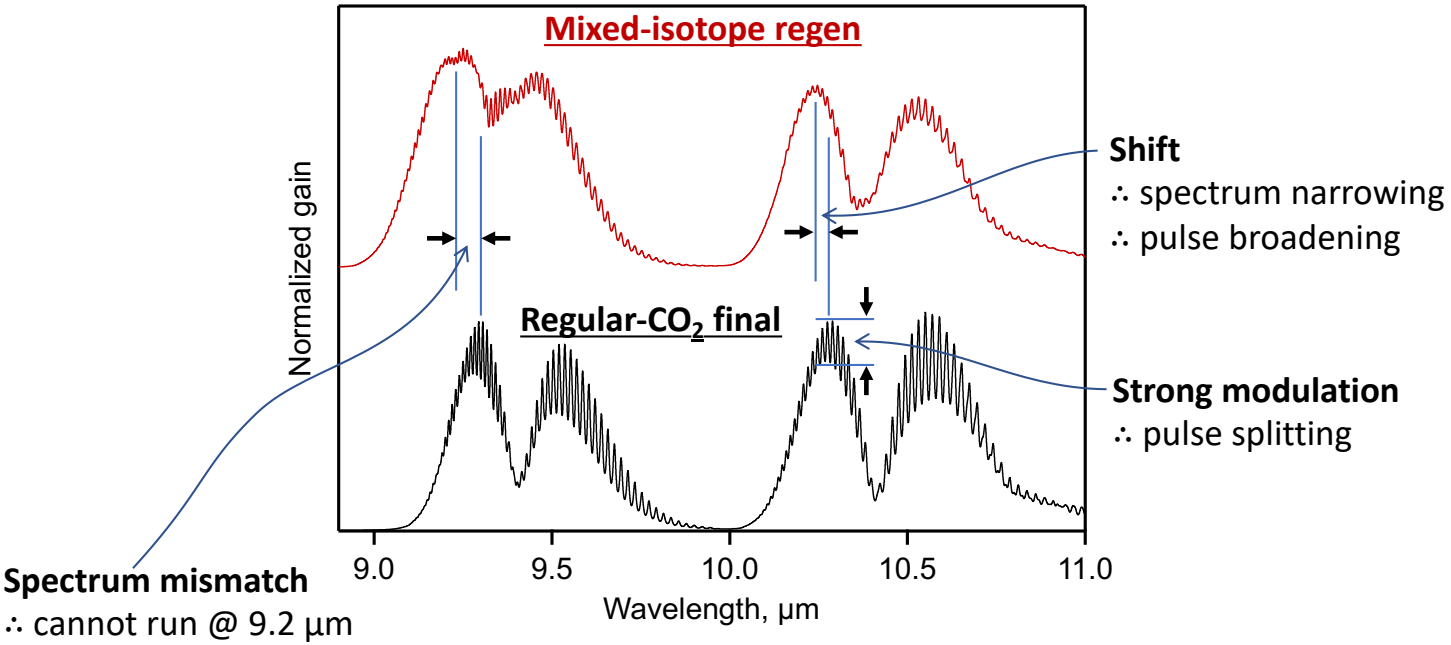
Mixed-isotope, high-pressure CO_2 amplifiers

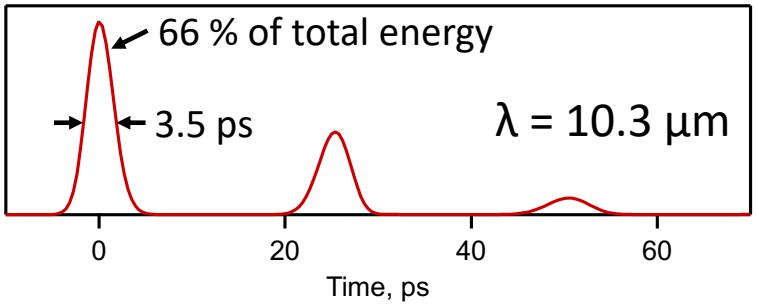


Regen
10 bar
CO_2: 0.3
N_2: 0.1
He: 9.6
^{18}O: 43 %

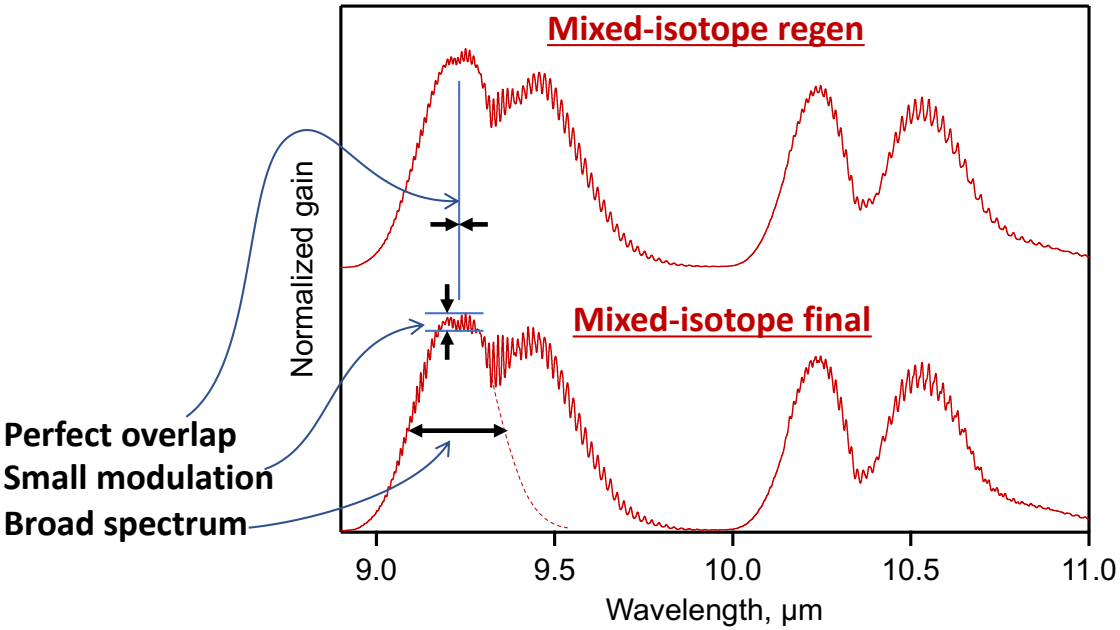
Final
8.25 bar
CO_2: 0.5
N_2: 0.25
He: 7.5
^{18}O: 47 %

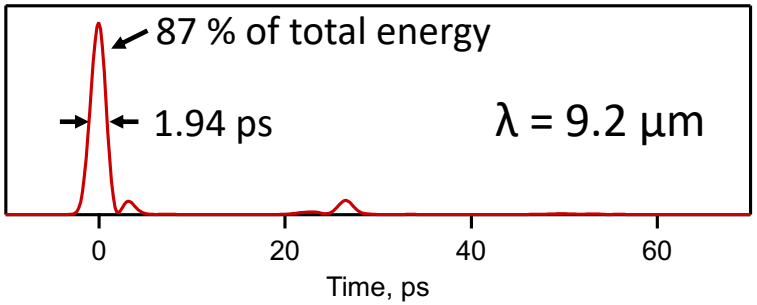
Old configuration (2010~2018)





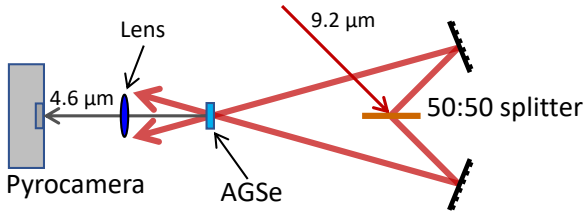
New configuration (since 2018)



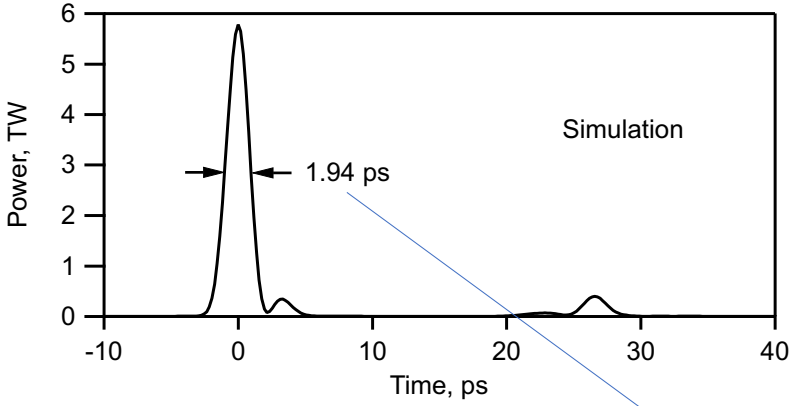


Pulse measurement procedure

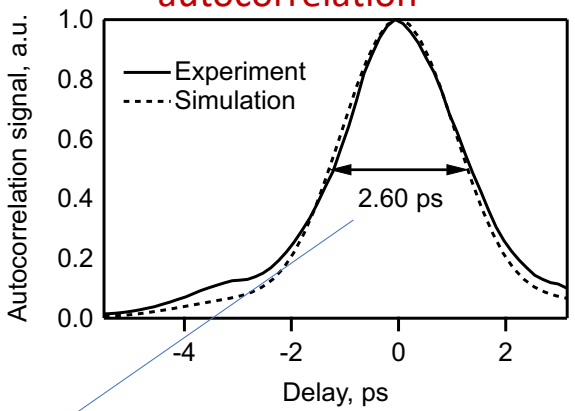
Single-shot autocorrelator



Expected pulse structure



Expected and measured autocorrelation



"De-convolution" $\tau = 1.94\ ps$, $\tau_{ac} = 2.60\ ps$ $\Rightarrow$ $\boldsymbol{\tau = 0.746\tau_{ac}}$