Study of laser-driven ion accelerators via ultra-fast optical and electron radiography of high-density plasmas at ATF

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Abstract

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL) combines a multi-terawatt picosecond long-wave infrared (LWIR) laser (~10 μm wavelength) with a synchronized high-brightness relativistic electron beam from a photocathode linac and near-infrared lasers for optical diagnostics. Of particular importance are high-density plasmas at or above the critical density, where the LWIR laser propagation abruptly terminates and energy is deposited within a narrow layer at the critical surface. The localized energy deposition produces large populations of hot electrons that generate strong charge-separation fields capable of accelerating ions and launching electrostatic shock waves, thereby generating dense ion bunches with picosecond duration and high charge density. The purpose of this study is to explore the possibility toward dedicated experimental platforms for fundamental plasma studies relevant to fusion energy, where detailed diagnostics can directly probe laser–plasma dynamics under controlled conditions.

Underlying Idea

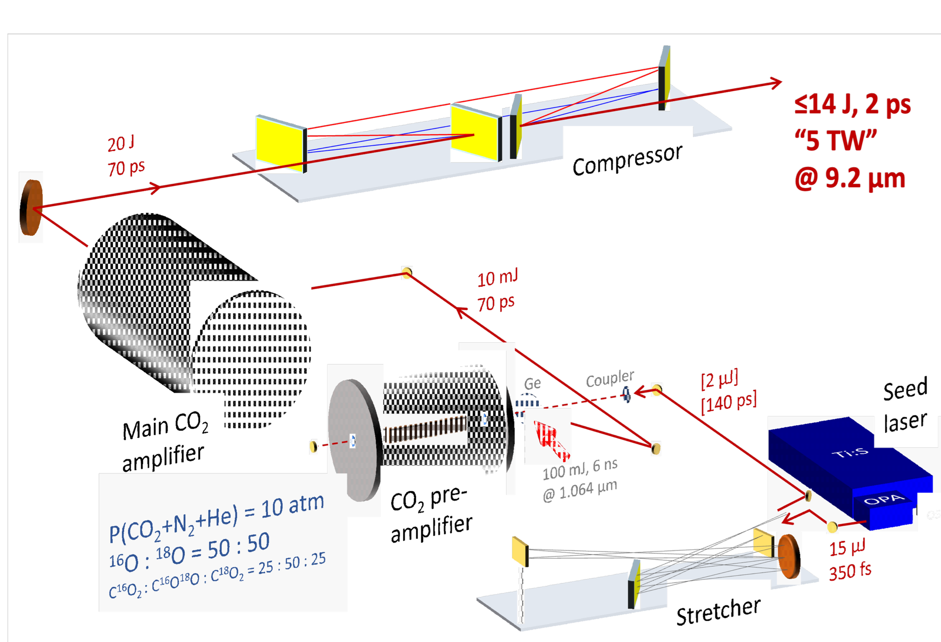
It is well established from particle-in-cell (PIC) plasma simulations that the physical picture of laser interaction with fully ionized plasma remains invariant when all relevant parameters are properly normalized to the laser frequency, ω. Specifically,

time $\tilde{t} = \omega t$, length $\tilde{x} = \frac{\omega}{c} x$,

plasma density $\tilde{n}_e = \frac{n_e}{n_{cr}} \propto \frac{1}{\omega^2} n_e$, EM field $a_0 \propto \frac{\sqrt{I}}{\omega}$,

When expressed in these normalized variables, simulation results are independent of the laser wavelength.

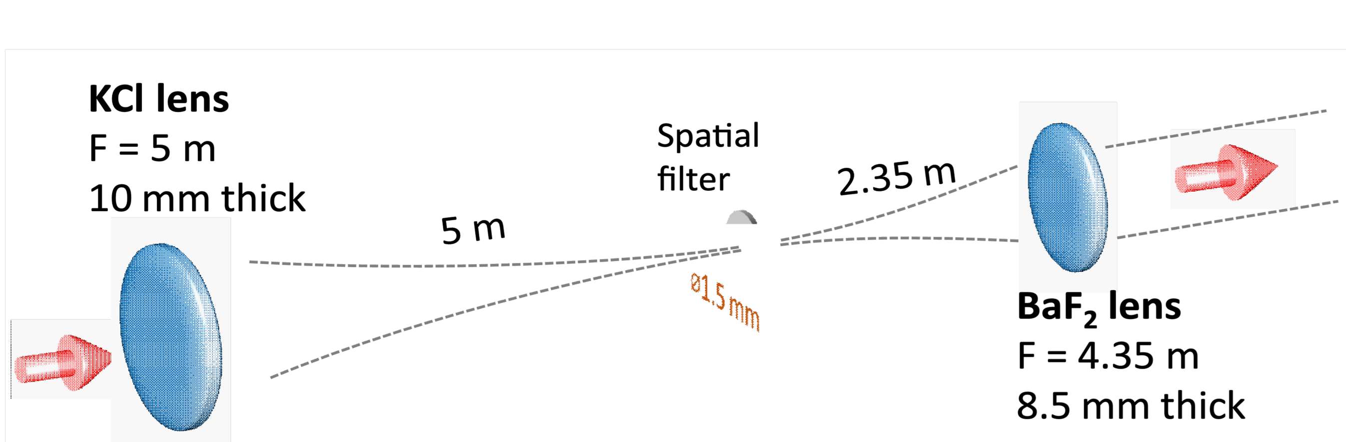
According to this similarity principle, a 10-μm laser can sustain laser–plasma interaction regimes that are qualitatively identical to those of a 0.35-μm laser, while requiring three orders of magnitude lower peak power and operating at three orders of magnitude lower plasma density. Consequently, laboratory-scale modeling experiments using currently available LWIR lasers, combined with fast, high-resolution optical diagnostics, can provide relevant and accurate insight into plasma processes that occur under the harsh conditions of super-intense UV lasers interacting with near–solid-density plasmas at the boundary of an imploding ICF target shell.



100-Joule CO_2 laser amplifier at BNL for future upgrades

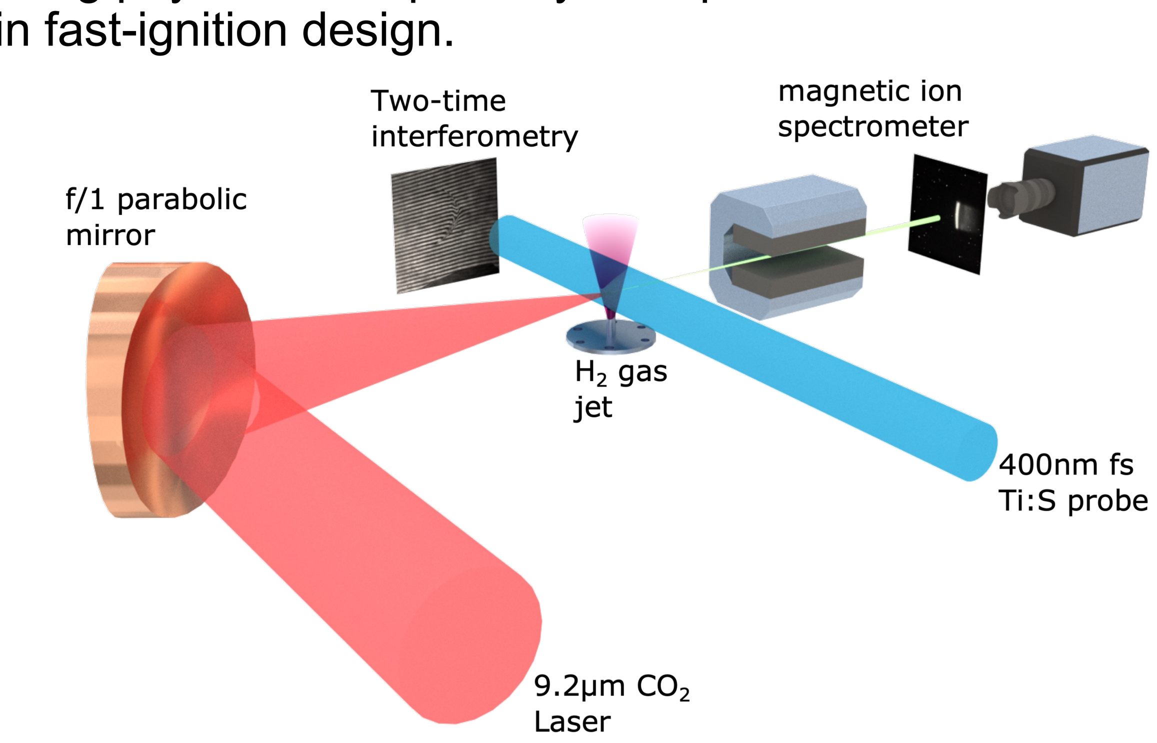
ATF LWIR Laser

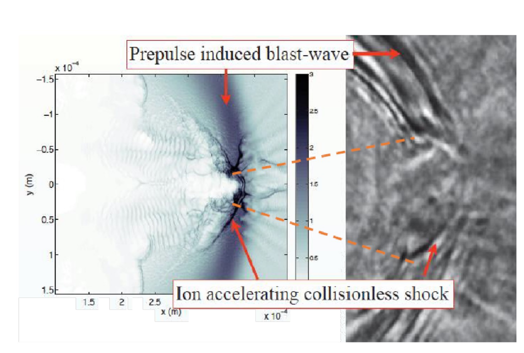
- A **hybrid gas/solid-state laser architecture** employs **high-pressure, mixed-isotope CO_2 gas amplifiers** seeded by a solid-state optical parametric amplifier (OPA).
- The first-ever implementation of **Chirped-Pulse Amplification (CPA) technique** for a molecular-gas laser. These advances enable record-high-intensity single short pulses in the LWIR.
- Currently, the system achieves intensities of ~10^{17} W/cm² at near-diffraction-limited focusing.
- For perspective, the ponderomotive effect on plasma electrons makes this intensity equivalent to ~10^{20} W/cm² for a 0.35-μm laser—deep into the relativistic regime.



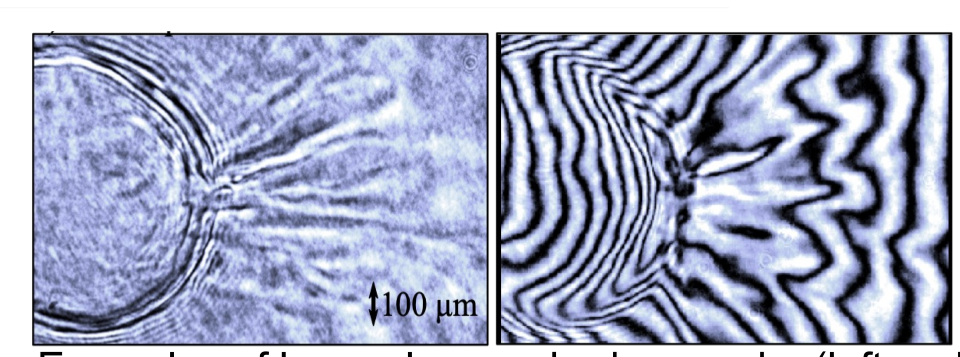
ATF Laser-Plasma Experiments

- Experiments conducted with LWIR drivers at reduced plasma density and laser intensity offer substantially improved diagnostic access compared with ignition-scale facilities, enabling direct observation of microscopic spatial structures, ultrafast dynamics, and instability evolution that are otherwise inaccessible.
- This approach complements large-scale facilities such as NIF and OMEGA by providing physical transparency and quantitative validation of models that underpin fast-ignition design.

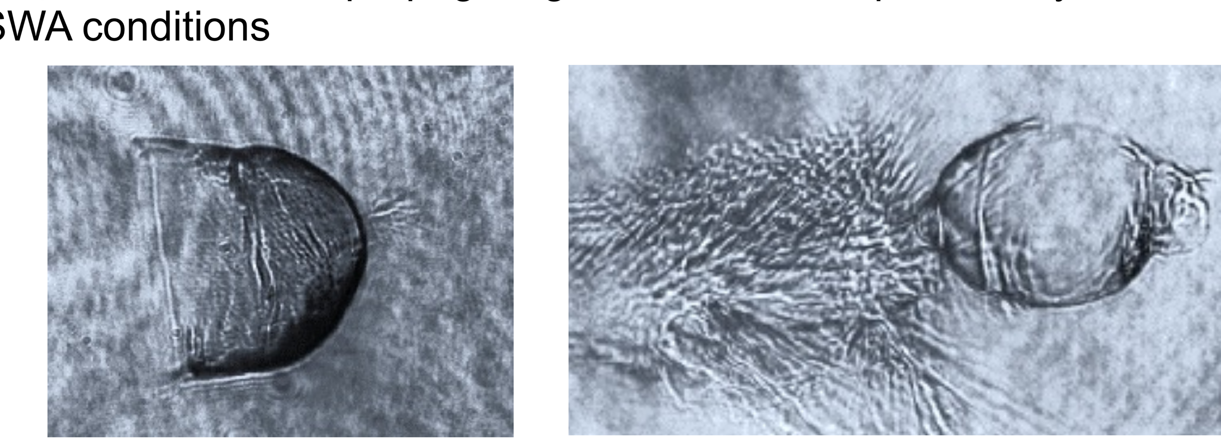




Simulated and experimental plasma profiles at SWA conditions



Examples of laser plasma shadowgraphy (left and bottom) and interferometry (right) experimentally obtained at ATF revealing electron filaments propagating from the critical plasma layer



- ATF is a leader in developing high-peak-power long-wave IR laser technology and using it for ion acceleration.
- Long-wavelength lasers are most efficient in producing hot electrons. $U_q = \frac{e^2 E^2}{4 m \omega^2}$
- As the result, 10-μm laser can provide equal electron energy but within 1000 times bigger plasma volume compared to 1-μm laser of the same power.
- Low critical plasma density allows driving ions out of gas enabling a novel regime of shock wave ion acceleration demonstrated and investigated at ATF. $n_{cr} = \frac{m_e \omega^2}{e^2}$

Future femtosecond laser upgrade