Development of a High Charge 10 GeV Laser Electron Accelerator

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Motivation

- **10+ GeV electron beams with controllable beam parameters are in demand for free electron lasers (FEL), muon radiography, and staging for HEP applications.**

Gas Jet Development

- **UMD has developed several generations of elongated supersonic gas jets for LWFA that have been employed at UMD, BELLA at LBNL, ALEPH at Colorado State University, and ELI Beamlines**
- **These developments enabled multi-GeV LWFA in low- density plasma waveguides, including recent 10 GeV results [1-6].**

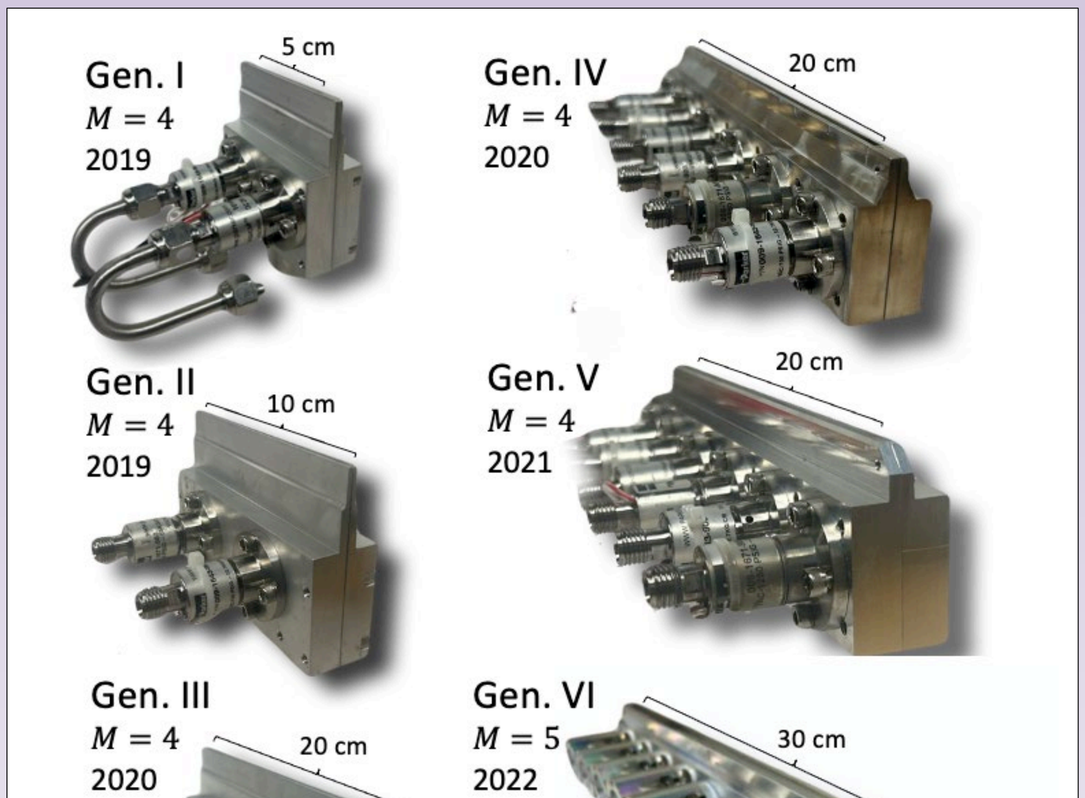

Fig. 1 from [1]. Generations of UMD gas jets. Gen. IV was used for the first demonstration of multi-GeV LWFA with all-optical plasma waveguides [4].

10 GeV, Multi-Joule Electron Beams

- **Our gas jet technology, channel benchmarking, and pulse propagation model has enabled two separate demonstrations of ~10 GeV electron acceleration [1,5].**
- **In the figures below, ~10 pC features are visible above 9 GeV extending beyond 10 GeV, generally injected by stage I.**
- **Stage II mode beating injects more charge varying between 200 pC to 1.4 nC in the 1-8 GeV range, producing electron beams with directly measured (through the spectrometer slit) laser energy → electron conversion efficiency of ~ 30%**

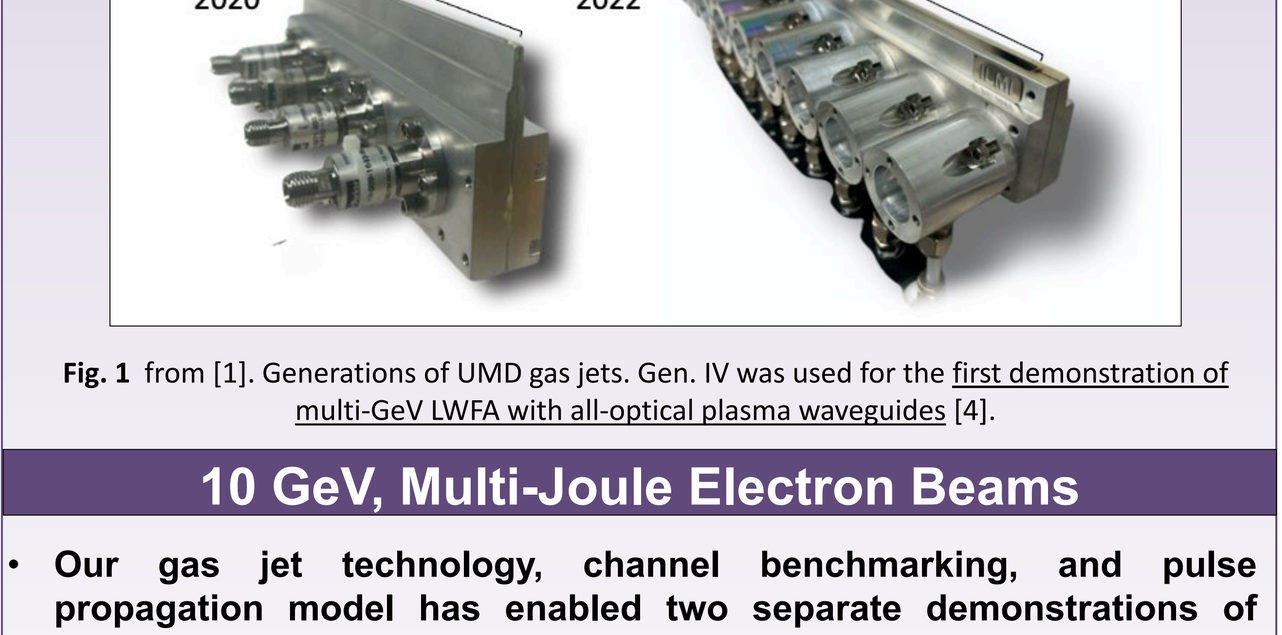

Fig. 4 from [1]. (a) Angle-resolved electron bunch spectra plotted on log colormap for 50 high energy shots; angular range for each spectral strip is 8 mrad. (b) Angle-integrated version of (a). Charge measurements are for the beam that has passed through the slit.

Benchmarking Hydrodynamic Plasma Waveguides

- **We've conducted two-color interferometry measurements and developed a self-consistent model for channel evolution.**
- **The propagation model (YAPPE) [2] generates electron temperature and density profiles, which are input as initial conditions to the hydrodynamic code (SPARC) [7] to drive the evolution.**

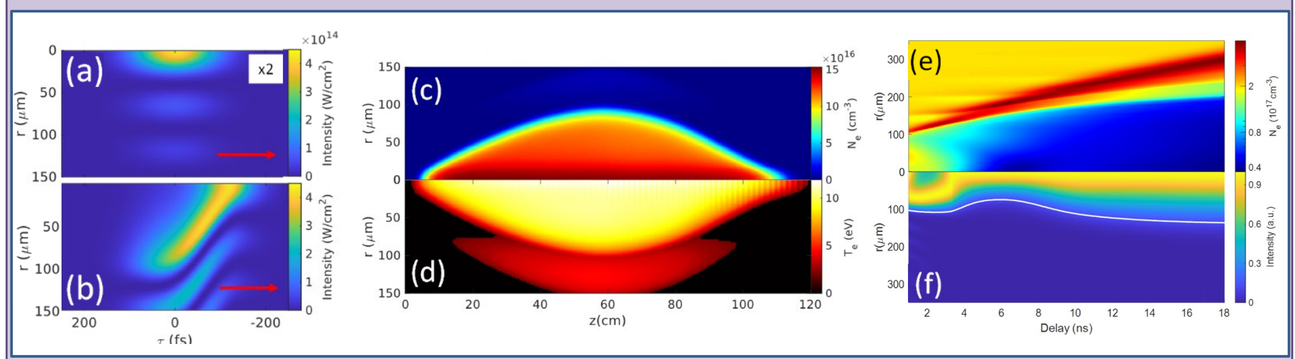

Fig. 2 from [2]. Modelling of meter-length plasma waveguide using YAPPE and SPARC results: intensity envelope at (a) $z = 4\,\mathrm{cm}$ and (b) $z = 60\,\mathrm{cm}$, (c) electron density, (d) electron temperature, (e) temporal evolution of waveguide, and (f) fundamental quasibound mode.

3-Stage Model of Relativistic Pulse Propagation

- **We present a 3-stage model of pulse evolution that correlates with electron injection and acceleration, including a new sustained mode beating effect that occurs whether or not the pulse is linearly matched to the waveguide [1,6].**
- **Stage I**: large amplitude oscillations due to linear mode mismatch.
- **Stage II:** lower amplitude beating in a ponderomotively modified channel.
- **Stage III:** pulse disperses, stretches, red-shifts and a_0 declines.

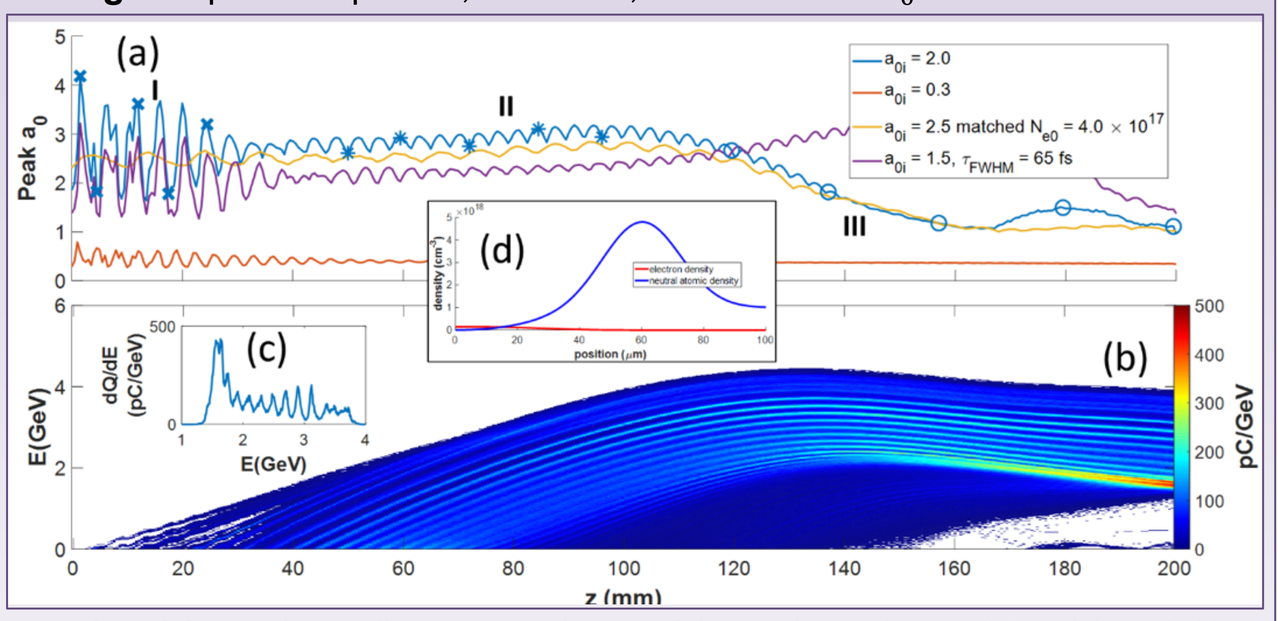

Fig. 3 from [6]. Particle-in-cell WarpX simulations of drive pulse evolution. **(a)** Peak laser field a_0 vs. propagation distance for: Blue ($a_{0i} = 2.0$), Purple ($a_{0i} = 1.5$), and Orange curve ($a_{0i} = 0.3$) all propagate in mismatched waveguide. Gold curve ($a_{0i} = 2.5$)—matched Gaussian input to channel. **(b)** Electron spectrum vs. propagation distance mapping to blue curve of (a). **(c)** Final integrated spectrum. **(d)** Simulation waveguide profile.

Development for Acceleration Beyond 10 GeV

- **To scale electron energies beyond 10 GeV, longer acceleration lengths and custom density profiles to allow rephasing are required.**
- **We've developed a modular, supersonic gas jet formed of 3.4-3.8 cm sections, and demonstrated a meter-long Bessel beam-generated plasma (Fig. 5(a)) [3]. This modular gas jet also allows control of each section via solenoid valve timing or flow rate (20 cm custom profile shown in Fig. 5(b)).**

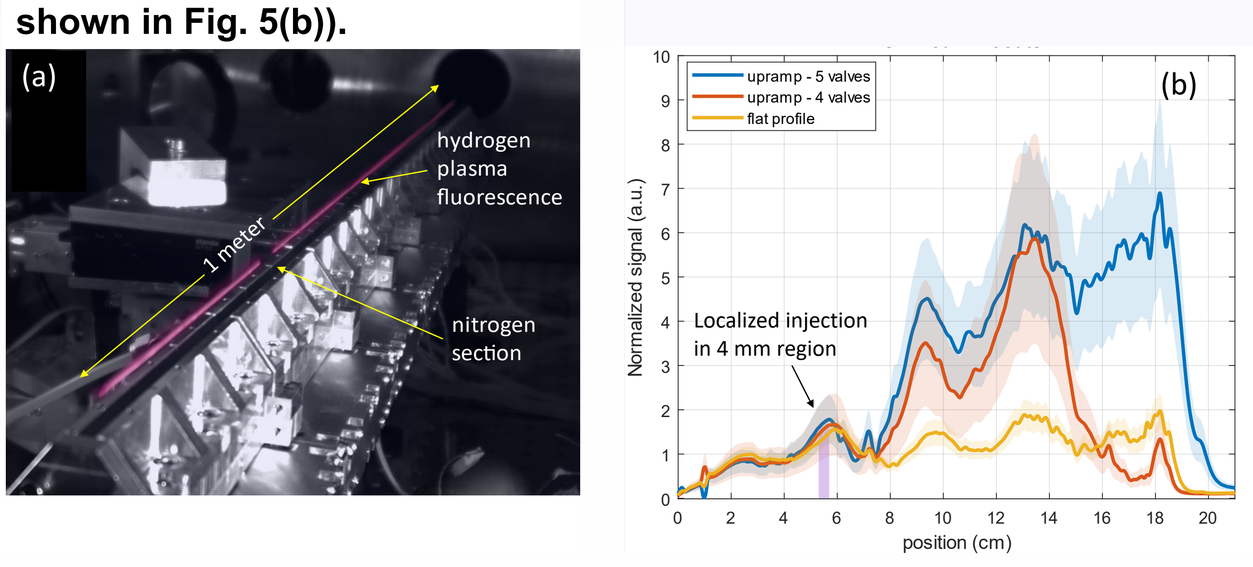

Fig. 5 from [3]. (a) 1 meter hydrogen plasma florescence generated using modular gas jet backed with 6.9 bar. One of 27 sections is backed with nitrogen, (b) Helium fluorescence of 20 cm flat (yellow) and up-ramp (orange and blue) density profiles of modular gas jet where valves have varied open times and backing pressures to enable customized density profile.

References

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This work used the CONTUR source code by L.F. Zavalan and A. Rona, based on the computer program by J.C. Sivells. This work is supported by the Department of Energy (DOE) (DE-SC0015516 and LaserNetUS DE-SC0019076/FWP#SCW1668, and DE-SC0011375); Office of Naval Research (ONR) (N00014-20-1-2233); and the National Science Foundation (NSF) (PHY2010511); ER is supported by NSF GRFP (Grant No. DGE 1840340). This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730 'I.FAST'.