Designing structured plasmas for next generation hadron and lepton accelerators

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HEP GARD Accelerator and Beam Physics: Workshop #2
(WG2: Modeling and Simulation Tools)

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Structured plasmas present unique opportunities for accelerators

- What are structured plasmas?
  - Any plasma system which is manipulated by energy deposition or beam (electron, ion, laser) interaction prior to a primary interaction (e.g. discharge capillaries, plasma ovens, plasma cells, ionized gas jets, etc.)
- Grand Challenge #2: How do we increase beam phase-space density by orders of magnitude?
  - Structured plasmas enable AAC particle beam sources to deliver improved beam phase-space densities
    - Higher charge, higher energy, reduced emittance, and improved energy spread
    - LPA, PWFA, structure-based, hybrid, and ion acceleration schemes each benefit from improved source design
    - Tailored plasmas may improve diagnostic capabilities for ultrashort beams
  - *Tremendous experimental progress in recent years. Future improvements will greatly benefit from long-time 3D MHD simulations to guide design and testing.*
- Grand Challenge #4: How do we develop predictive "virtual particle accelerators"?
  - Specialized tools are needed to model structured plasmas for next generation accelerators
  - MHD simulations are the best approach to capturing the essential physics

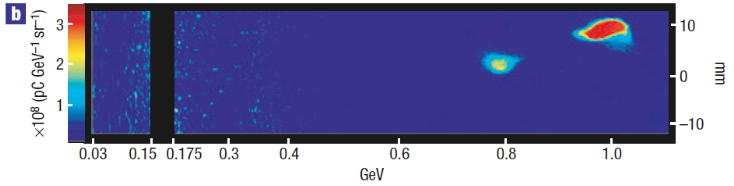
A renewed emphasis on the development and integration of MHD codes with traditional computational tools will broadly benefit the accelerator community

Capillary discharge waveguides improve LPA beam energy and quality

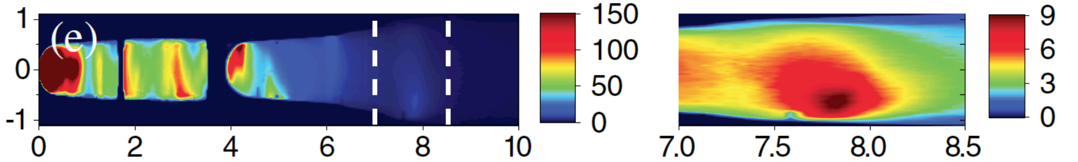
- Ohmic heating generates slowly evolving parabolic profile which may be matched to a Gaussian laser spot

$$n_p(r) = n_0 + \Delta n \frac{r^2}{W_0^2}$$

- Matching preserves laser spot and mode structure over many Rayleigh ranges
    - Longitudinal density tapering combats dephasing

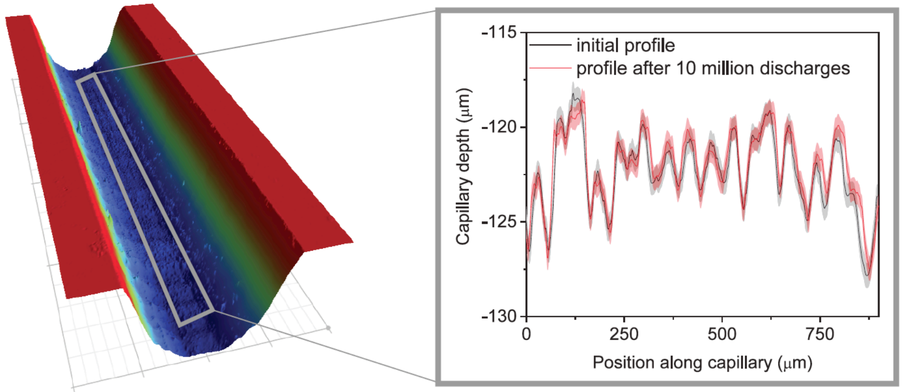


Nat. Phys. **2**, 696-699 (2006)



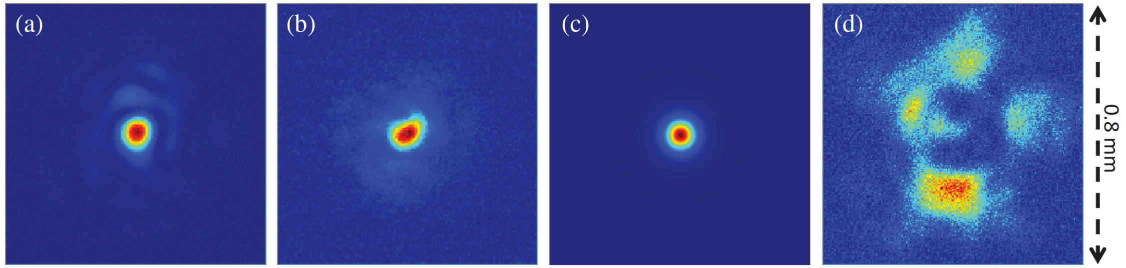
Phys. Rev. Lett. **122**, 084801 (2019)

Suitable for kHz operation with long lifetimes



J. Appl. Phys. **119**, 033302 (2016)

Laser sub-channel formation improves guiding



Vacuum focus
z=0 cm

Capillary exit
z=20 cm (experiment)

Capillary exit
z=20 cm (simulation)

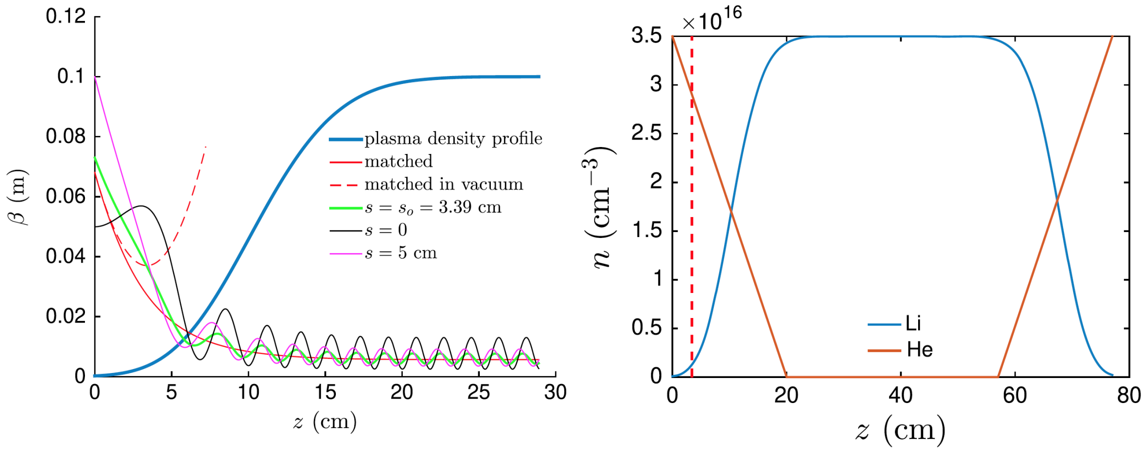
Vacuum
z=5.4 cm

Phys. Rev. Lett. **122**, 084801 (2019)

Tailored plasmas may preserve emittance, reduce energy spread in PWFAs

Plasma ramps mitigate emittance growth

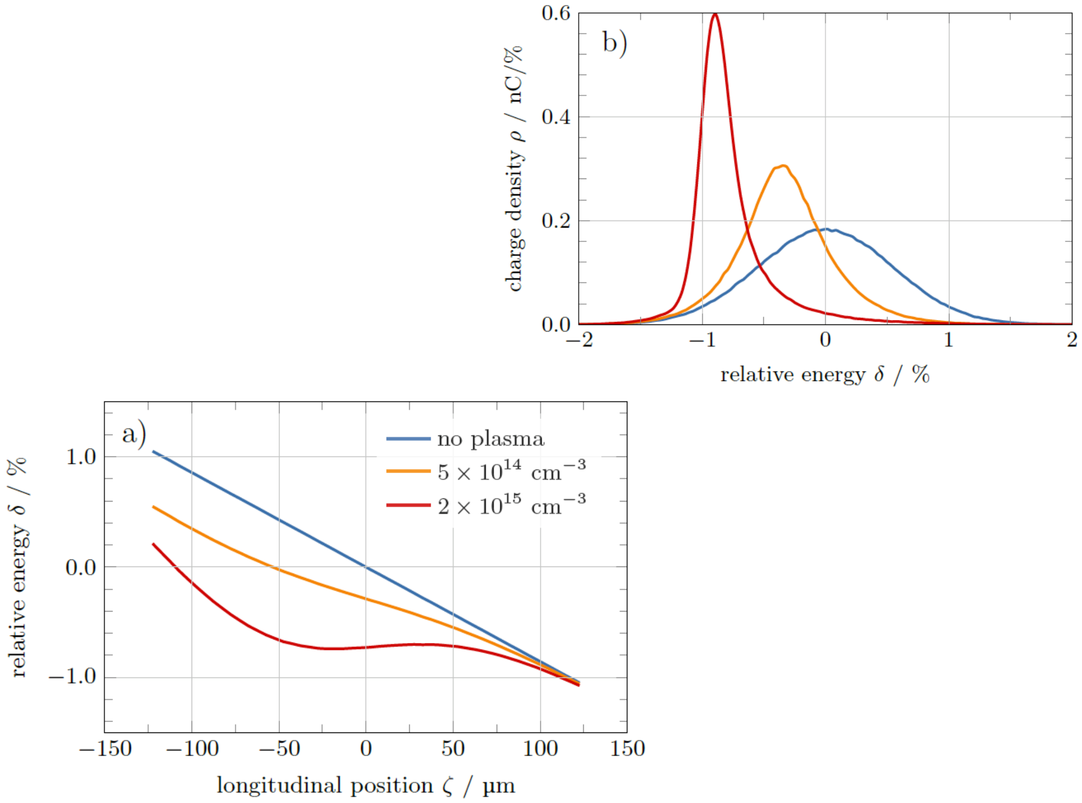
- Adiabatic ramping of plasma density enables beam matching at entrance, exit of plasma
- Valuable for all staged plasma accelerators
- Use of Helium buffer gas may spoil emittance preservation at high intensities.
- Tailoring of density mixture to beam parameters could mitigate additional growth



Phys. Rev. Accel. Beams **23**, 011302 (2020)

Plasmas for tunable energy de-correlation

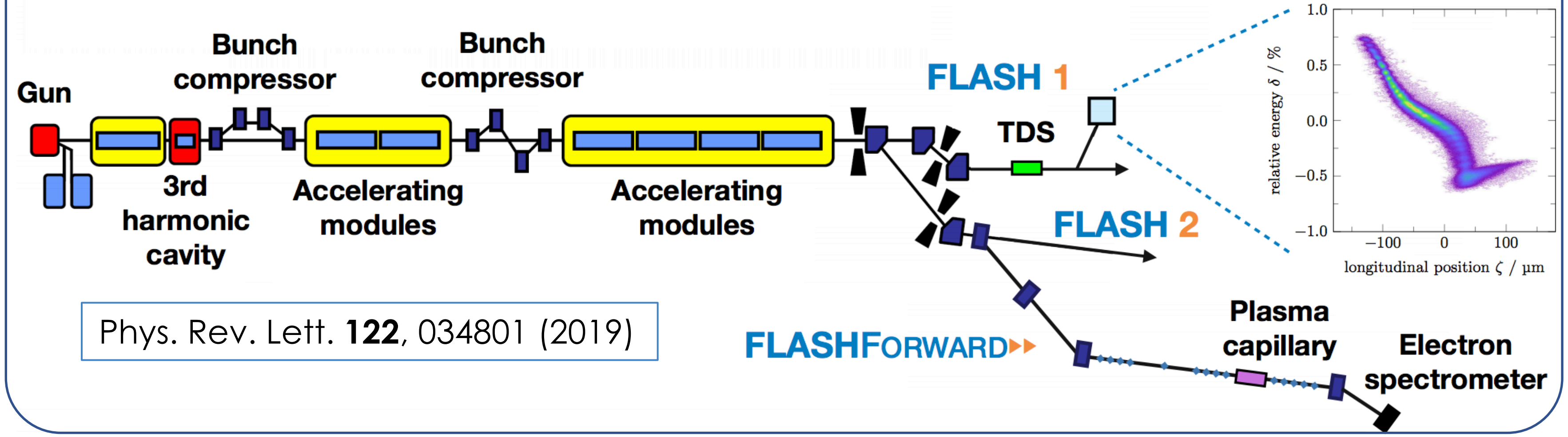
- Wake response is more effective than structure
- Adjust for bunch length, chirp via plasma density
- Chirps may be desirable for witness transport



Phys. Rev. Lett. **122**, 034801 (2019)

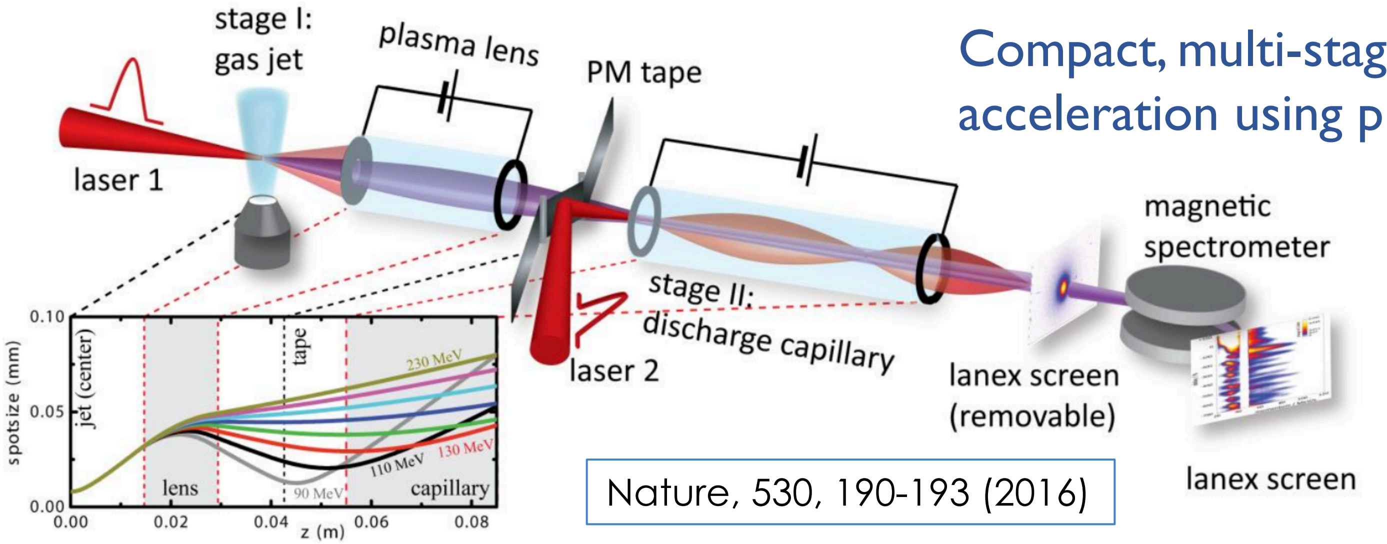
Active plasma lenses deliver orders of magnitude improvements in focusing

Flexible beam transport of high energy beams, and high divergence beams



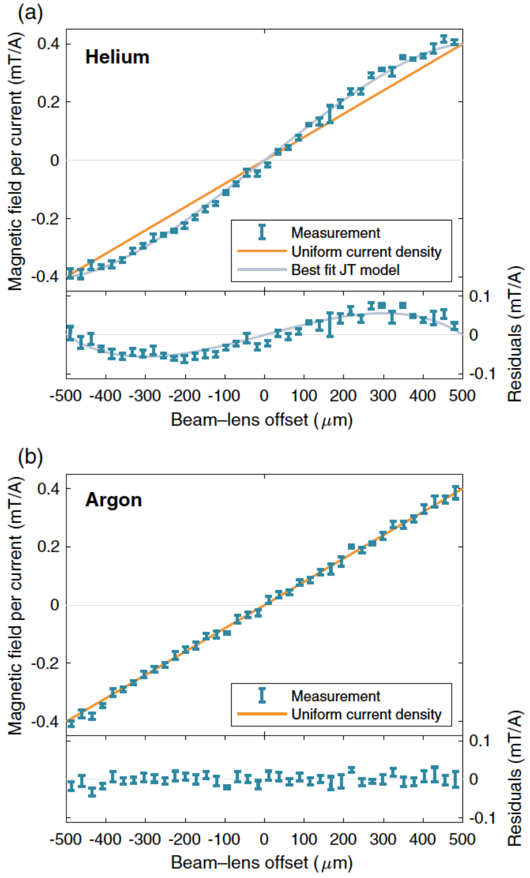
Phys. Rev. Lett. **122**, 034801 (2019)

Compact, multi-stage plasma acceleration using plasma lens



Nature, 530, 190-193 (2016)

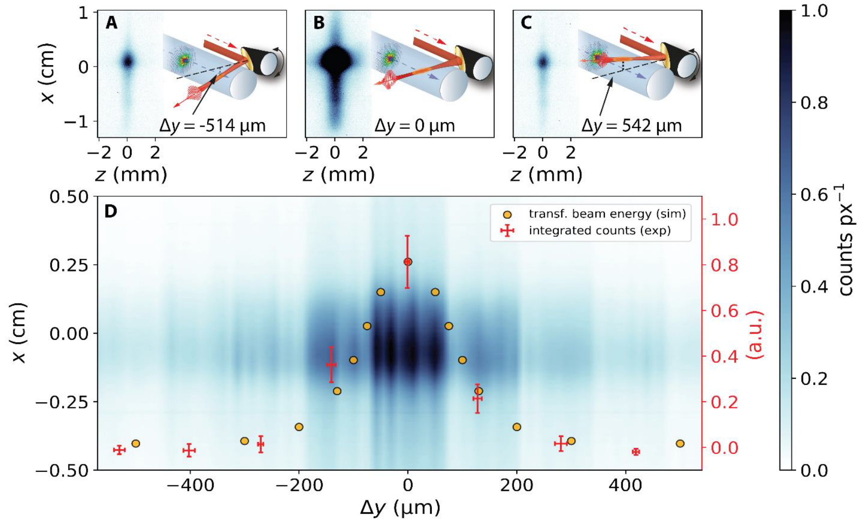
Careful selection of gas, discharge parameters mitigates aberrations



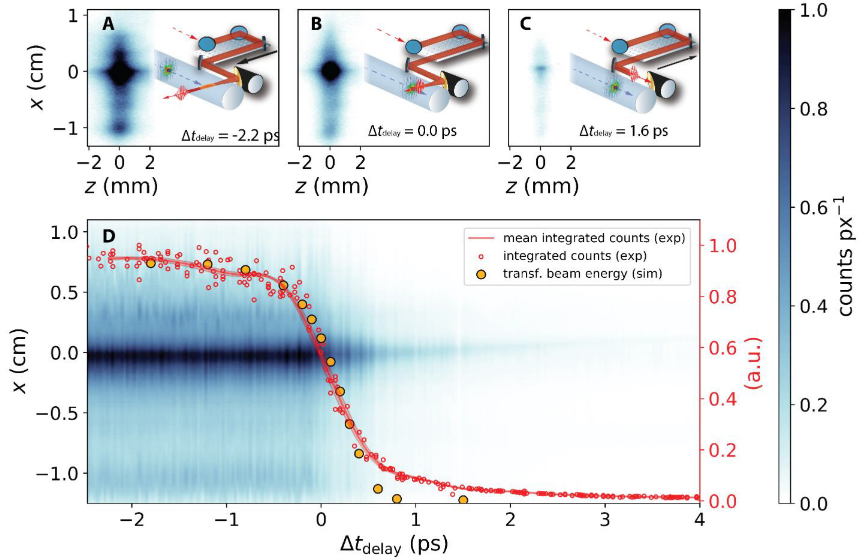
Phys. Rev. Lett. **122**, 129901 (2019)

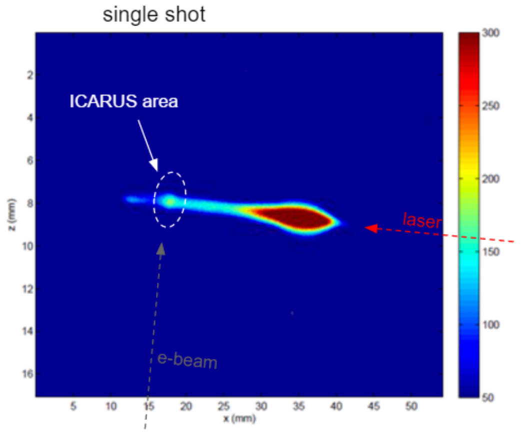
Novel non-destructive diagnostics can leverage plasma tailoring

- Plasma afterglow diagnostics enable micron/fs-scale spatio-temporal synchronization
    - Laser, electron-beam overlap for highest fidelity
    - Complementary to hybrid AAC schemes
- Sensitivity to initial density, temperature
- Recombination dynamics are essential
    - Temperature and density distribution may be nontrivial
    - PIC provides initial conditions, MHD provides long-term dynamics

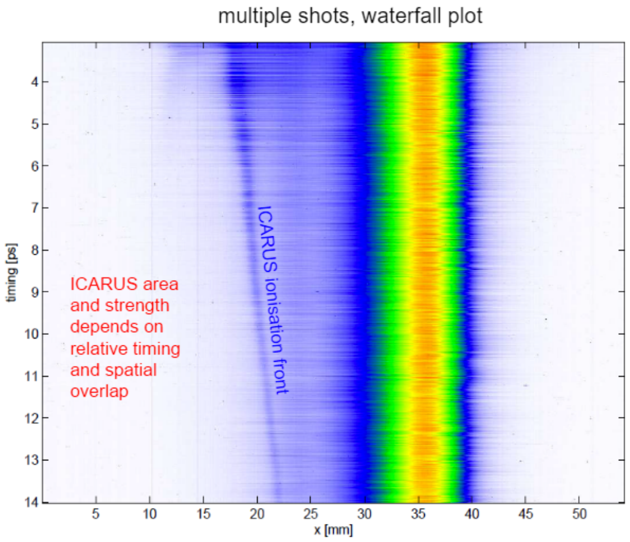


arXiv:1908.09263 [physics.plasm-ph]





Courtesy B. Hidding

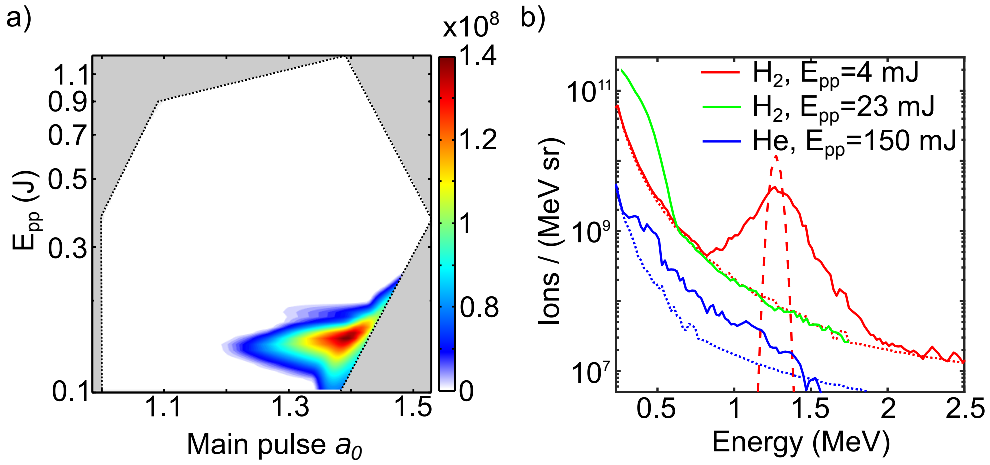


Plasma target shaping enables advanced ion acceleration schemes

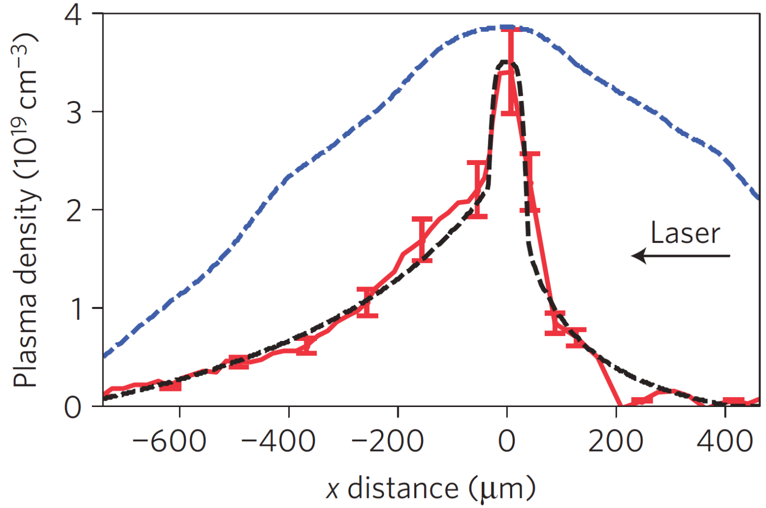
- Laser energy deposition for flexible target shaping
  - Symmetric, robust, reproducible density profile

$$\frac{n}{n_0} = \frac{\gamma+1}{\gamma-1} \qquad \gamma \approx 1.3 - 1.4$$

  - Controllable via gas parameters (n_0, radius, valve profile) and laser parameters (pulse energy, timing, focal position)
- Applications for advanced acceleration schemes
  - Ions: Local density steepening for $n > n_c$
    - Improve energy transfer from main laser pulse
    - Modulate ion acoustic velocity to narrow energy spread in collisionless shock acceleration
    - Modulate hole-boring velocity for radiation pressure acceleration
  - Electrons: localize injection point from high density region
  - Complementary to existing schemes (knife edge, supersonic gas jet)
- High sensitivity to laser and gas parameters + timing



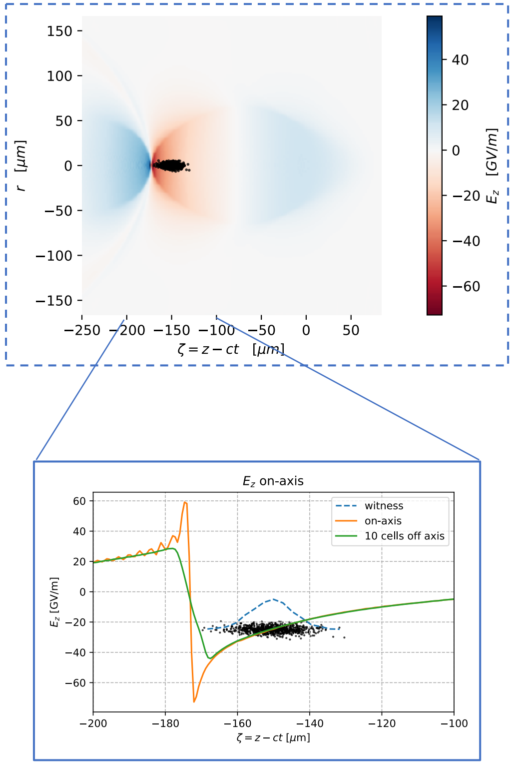
Phys. Rev. Lett., **115**, 094802, (2015).

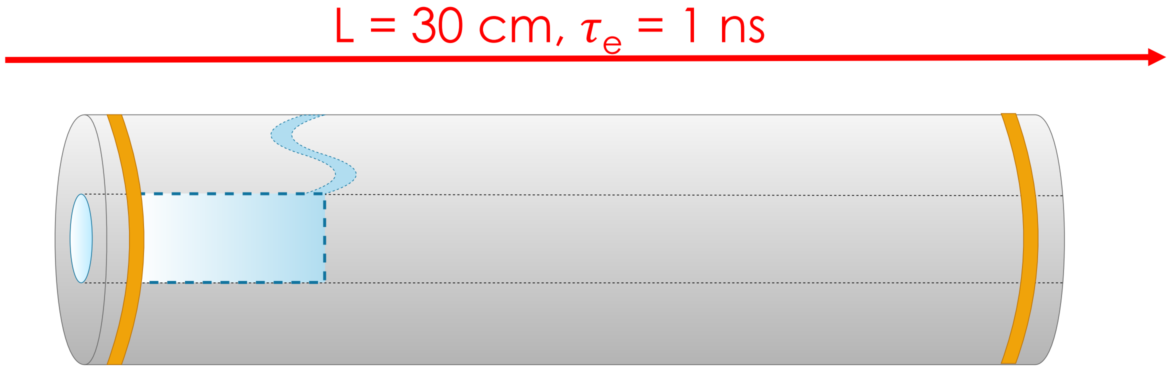


Nat. Phys., **8**, 95-99 (2012).

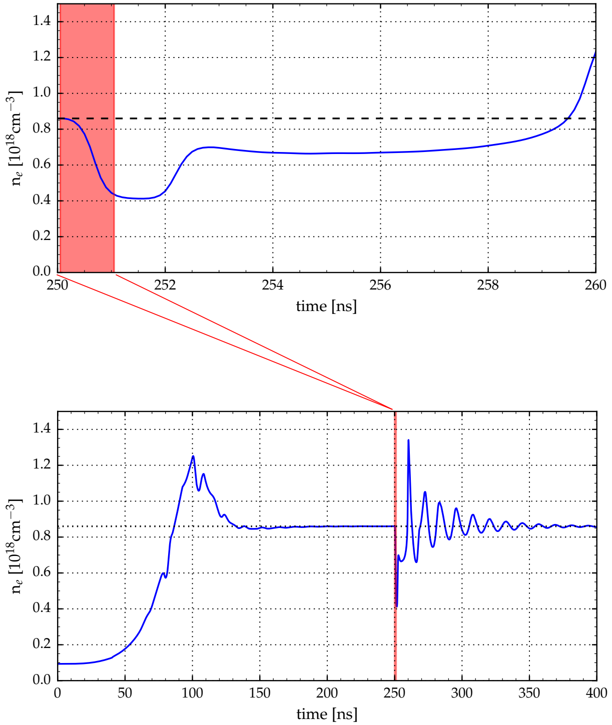
Dedicated MHD software is required to model plasma systems (I)

- Structured plasma systems are well suited for magneto-hydrodynamic modeling
  - Length Scales (cm–scale) far exceed computational feasibility for PIC simulations
  - Duration of evolution (ns) similarly require many hundreds of thousands of steps
  - Quantities of interest (density, temperature, ionization state) are more suited for fluid than kinetic description
  - Established efforts in HEDP community demonstrate viability of these tools for a range of plasma phenomena





PIC Region of Interest: [500 μm x 500 μm]



Dedicated MHD software is required to model plasma systems (II)

Core Utilities: Hydrodynamics and Equation of State

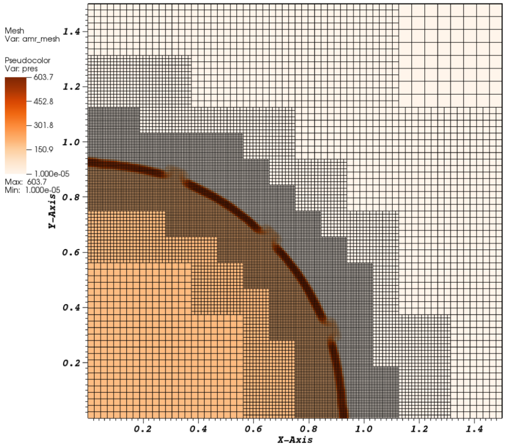
$$\left\{ \begin{array}{c} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \\ \frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) + \nabla P_{\mathrm{tot}} = 0 \\ \frac{\partial}{\partial t}(\rho E_{\mathrm{tot}}) + \nabla \cdot [(\rho E_{\mathrm{tot}} + P_{\mathrm{tot}})\boldsymbol{v}] = Q_{\mathrm{las}} - \nabla \cdot \boldsymbol{q} \end{array} \right\}$$

Multi-Temperature Model accounts for internal energy discrepancies

$$\left\{ \begin{array}{c} \frac{\partial}{\partial t}(\rho e_{\mathrm{i}}) + \nabla \cdot (\rho e_{\mathrm{i}} \boldsymbol{v}) + P_{\mathrm{i}} \nabla \cdot \boldsymbol{v} = \rho \frac{c_{v,\mathrm{e}}}{\tau_{ei}}(T_{\mathrm{e}} - T_{\mathrm{i}}) \\ \frac{\partial}{\partial t}(\rho e_{\mathrm{e}}) + \nabla \cdot (\rho e_{\mathrm{e}} \boldsymbol{v}) + P_{\mathrm{e}} \nabla \cdot \boldsymbol{v} = \rho \frac{c_{v,\mathrm{e}}}{\tau_{ei}}(T_{\mathrm{i}} - T_{\mathrm{e}}) - \nabla \cdot \boldsymbol{q}_{\mathrm{e}} + Q_{\mathrm{abs}} - Q_{\mathrm{emis}} + Q_{\mathrm{las}} \\ \frac{\partial}{\partial t}(\rho e_{\mathrm{r}}) + \nabla \cdot (\rho e_{\mathrm{r}} \boldsymbol{v}) + P_{\mathrm{r}} \nabla \cdot \boldsymbol{v} = \nabla \cdot \boldsymbol{q}_{\mathrm{r}} - Q_{\mathrm{abs}} + Q_{\mathrm{emis}} \end{array} \right\}$$

Structural Utilities: Geometry, Grid, Boundaries

- Geometries: 1D, 2D, RZ, 3D
  - Cylindrical symmetry is common
- Grid: structured or conformal mesh
  - Tradeoffs between speed and fidelity, especially at boundaries
  - Adaptive mesh refinement can ameliorate concerns with a structured mesh
- Electromagnetic fields require ”extra” work
  - Compute on a separate mesh
  - Balance between explicit, implicit integration
- Flexible boundaries simplify simulations
  - For capillary, current discharge may be specified by B_θ at capillary wall



Energy Deposition: Ohmic and Laser Heating

Plasma resistivity described by Spitzer

$$\eta_\perp = \frac{4\sqrt{2\pi}}{3} \frac{Z e^2 m_e^{1/2} \ln \Lambda}{(4\pi\epsilon_0)^2 (k_B T_e)^{3/2}} F(Z)$$

Laser and radiation deposition often described by Inverse Bremmstrahlung

$$P_{\mathrm{loss}} \propto e^{-\int \nu_{ib}(t)dt} \qquad \nu_{\mathrm{ib}} \approx \frac{4}{3}\left(\frac{2\pi}{m_e}\right)^{1/2} \frac{n_e Z e^4 \ln \Lambda}{(k_B T_e)^{3/2}}$$

Dissipation: Heat exchange, conduction, radiative diffusion

Proper treatment of conductivity must include surface temperature dependence

$$\frac{\partial e_{\mathrm{i}}}{\partial t} = \frac{c_{v,\mathrm{e}}}{\tau_{ei}}(T_{\mathrm{e}} - T_{\mathrm{i}}) \qquad \frac{\partial e_{\mathrm{e}}}{\partial t} = \nabla \cdot K_{\mathrm{e}} \nabla T_{\mathrm{e}}$$

$$\frac{\partial e_{\mathrm{e}}}{\partial t} = \frac{c_{v,\mathrm{e}}}{\tau_{ei}}(T_{\mathrm{i}} - T_{\mathrm{e}})$$

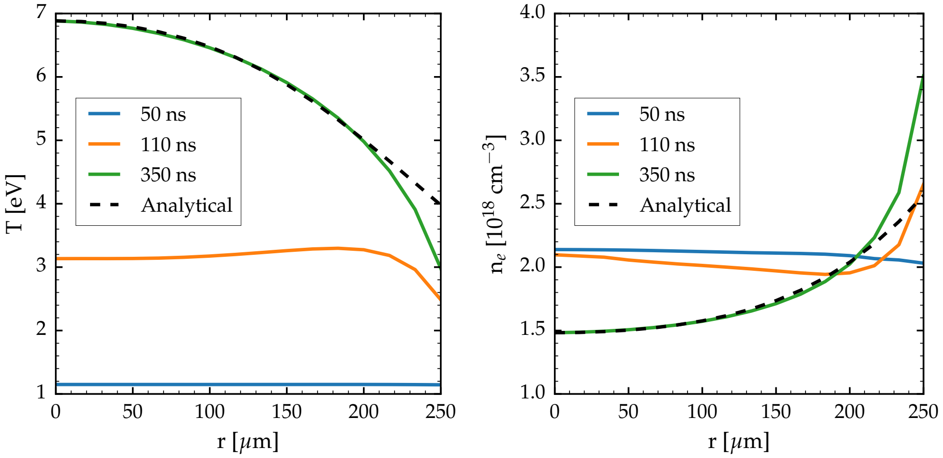
Radiation effects may be relevant for HEDP applications, but are minimal here

$$\frac{\partial u_{\mathrm{g}}}{\partial t} + \nabla \cdot (u_{\mathrm{g}} \boldsymbol{v}) + \left(\frac{u_{\mathrm{g}}}{e_{\mathrm{rad}}\rho}\right) P_{\mathrm{r}} \nabla \cdot \boldsymbol{v} = -\nabla \cdot \boldsymbol{q}_{\mathrm{g}} + Q_{\mathrm{emis,g}} - Q_{\mathrm{abs,g}}$$

Recent efforts demonstrate good agreement with theory and experiment

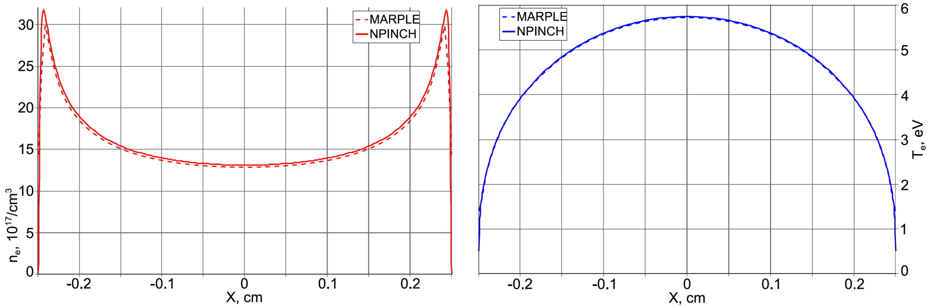
2D and 3D Capillary Benchmarks

FLASH R-Z simulations agree with one-dimensional theory



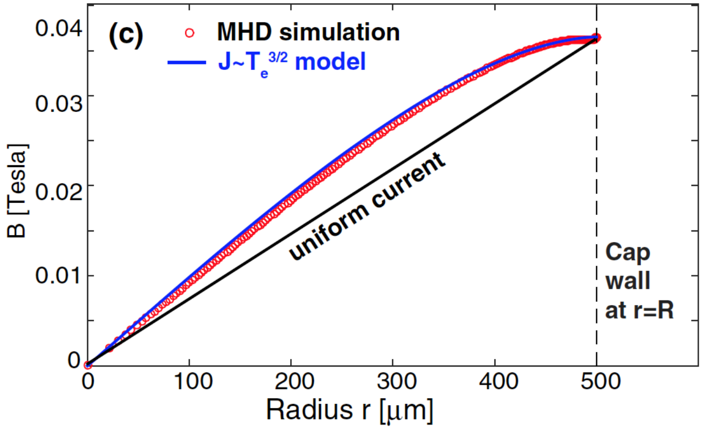
Cook et al. Proc. EAAC 2019, (in submission)

MARPLE 3D simulations show good agreement with same theory



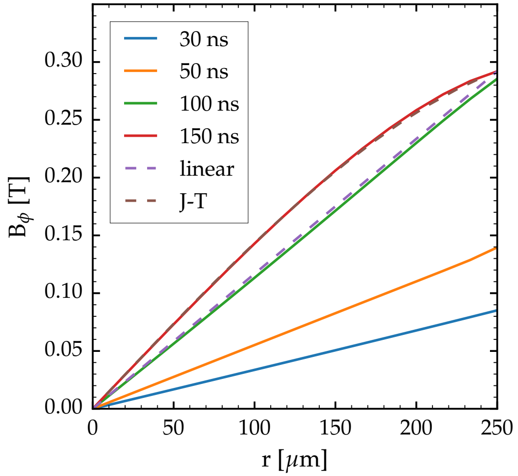
Phys. of Plasmas, **24**, 083109, (2017).

Predicting Lens Aberrations



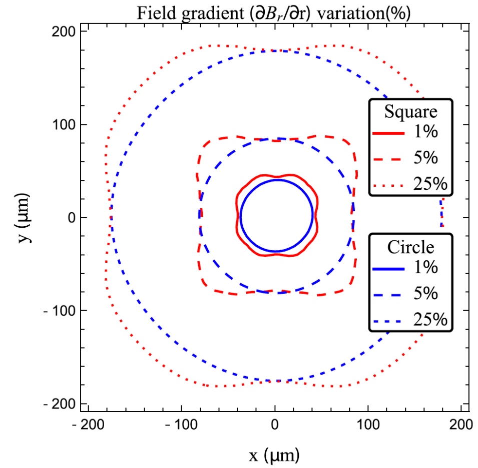
Phys. Rev. Accel. Beams, **20**, 032803, (2017).

Recent R-Z simulations show agreement (FLASH)

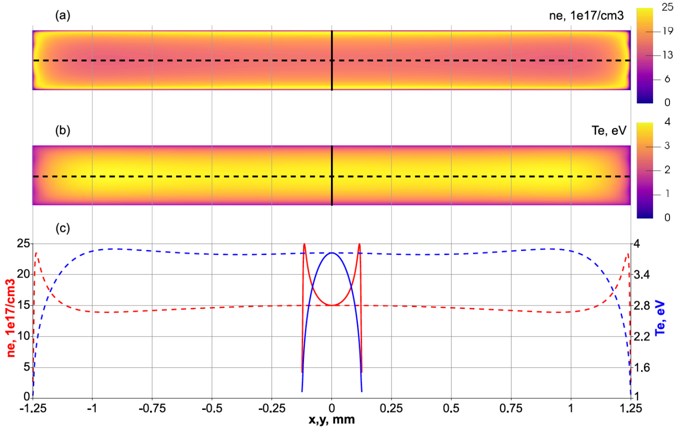


Cross-sectional variations

Square cell maximizes lens aperture (MARPLE)



Asymmetric for flat beam transport (MARPLE)

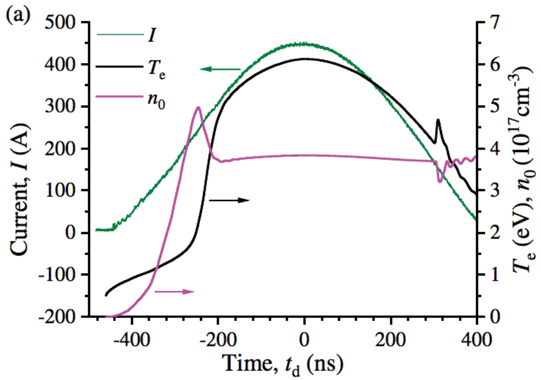


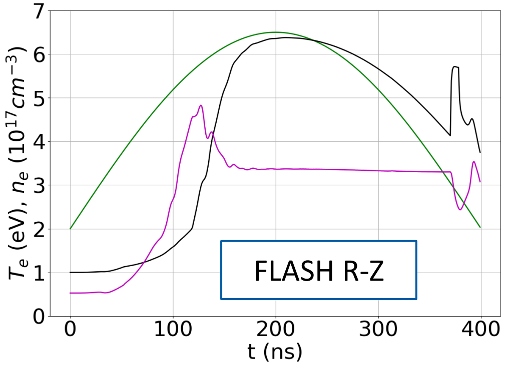
Phys. of Plasmas, **24**, 083109, (2017).

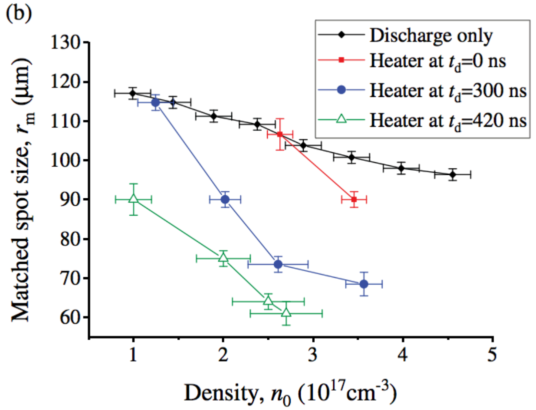
Laser energy deposition capabilities broaden simulation applications

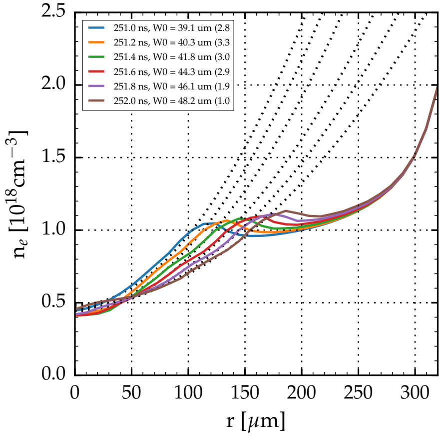
Modeling of laser-heater supports recent experimental results at BELLA

- Reduction in on-axis density, corresponding spot size
- Timing and evolution show good agreement with scans of heater laser timing





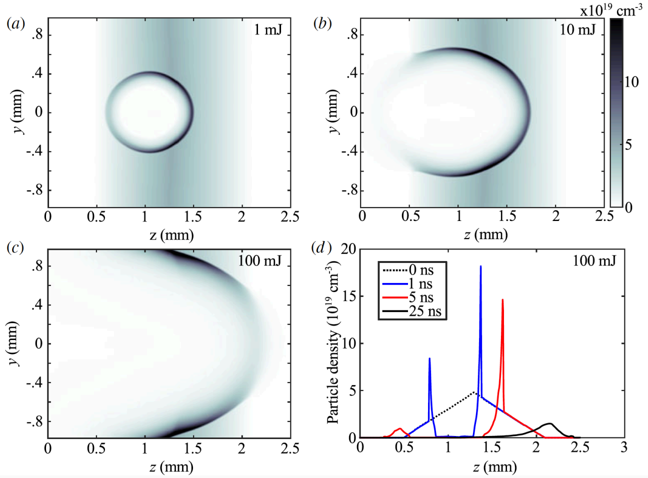




Phys. Rev. Lett. **122**, 084801 (2019)

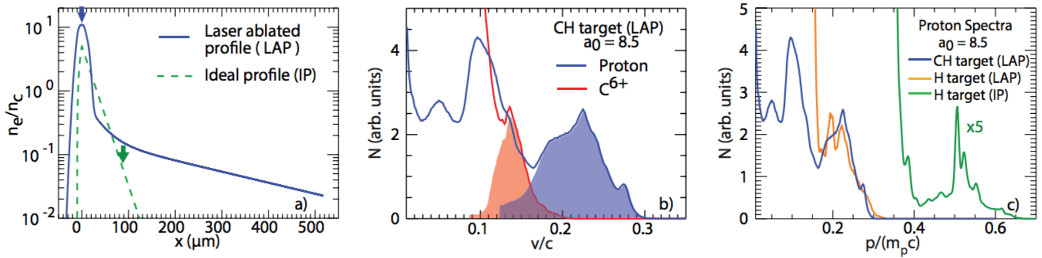
Simulated laser-deposition for near-critical density targets supports ion acceleration

- Laser deposition in gas controls density up-ramp



J. Plasma Phys., **82**, 415820101 (2016).

- Laser ablation of foil controls density down-ramp



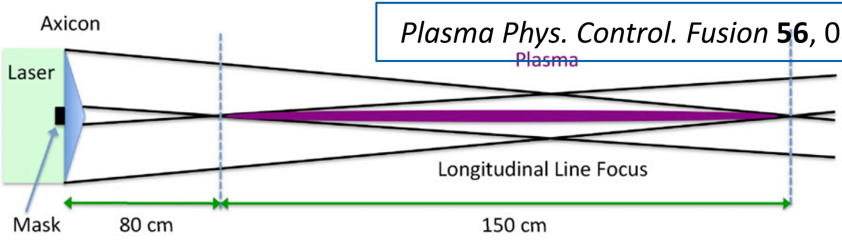
Phys. Rev. Accel. Beams, **21**, 103401 (2018).

New technologies, open questions motivate specialized demands on MHD

Improve energy deposition mechanisms

- Tunneling ionization for pre-ionized plasma channels

Plasma Phys. Control. Fusion **56**, 084011 (2014).

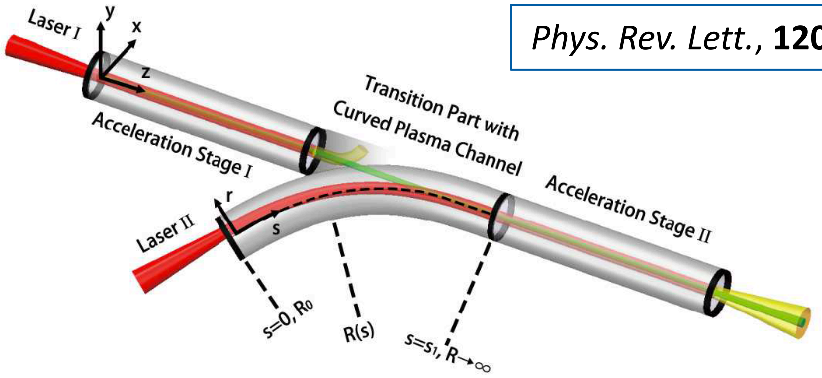


- Integrated self-consistent laser propagation
  - Some studies address through coupling to external codes for envelope propagation

Flexible geometry and boundary capabilities

- Creative geometries may address staging obstacles

Phys. Rev. Lett., **120**, 154801 (2018).



Non-LTE Physics, EOS considerations

- Discharge physics are not well described by LTE, yet may impact long-term capillary dynamics
  - EOS models should applied carefully for low-temperature systems
- Can MHD be adapted to study long-term plasma oscillations?
  - Current efforts combine PIC and fluid codes, but are extremely computational demanding

arXiv:2001.09401 [physics.plasm-ph]

Multi-species systems for novel plasma sources

- Optimization of buffer gases for plasma oven
- LIT/HIT mixtures for Ionization injection, Plasma Torch or Trojan Horse schemes
  - Can capillaries be used for this application in lieu of ovens or laser pre-ionization?
  - Recombination, excitation, and afterglow considerations remain

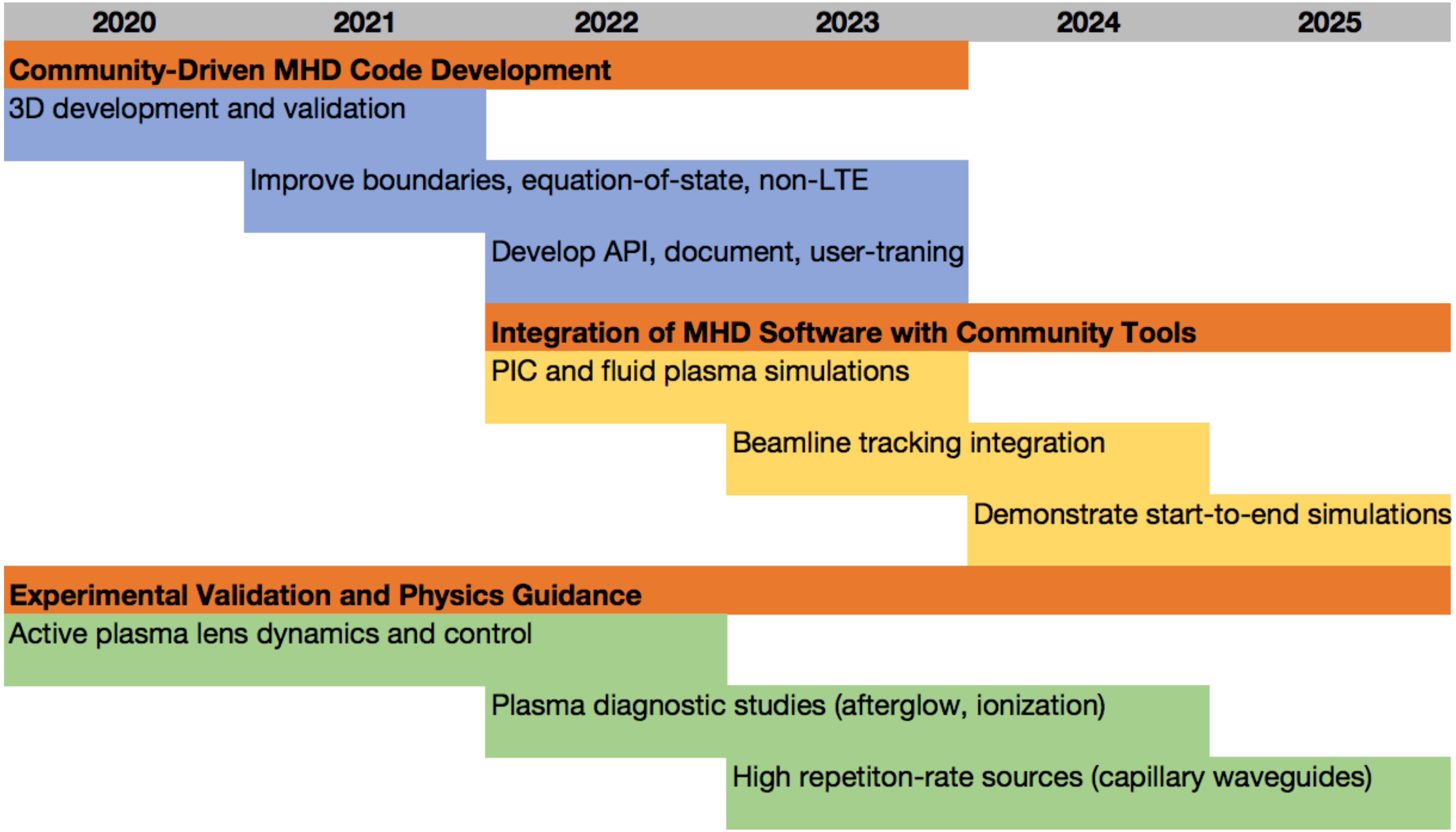
Nat. Phys, **15**, 1156-1160 (2019)

How do we bring MHD into mainstream for designing plasma structures?

1. Open-source, accessible MHD software for 3D plasma systems
   - Documentation and API should follow community standards (e.g. *PICMI*)
   - Modular, archetypal development to support non-expert use (especially critical in cases of experience gap)
   - Enhancements to boundary conditions and geometry to support new configurations
   - Leverage modern techniques (AMR, implicit solvers) and modern architectures (GPU, exascale) to reduce computational expense for 3D simulations
   - Lack of community expertise in MHD will require technology transfer, education
2. Integration with community tracking and PIC codes
   - Piece-wise coupling for beamline modelling: map-based or matrix-based beamline tracking (*elegant, OPAL, etc.*)
   - Tightly-coupled modality for plasma source design: run MHD in tandem with PIC
   - Adoption of standard workflows, I/O, and machine-agnostic execution will be required
3. Experimental validation of advanced features
   - Understand non-LTE dynamics in capillary waveguide and lens systems
   - Improvements in energy deposition to support additional kinetics, tunneling ionization
   - Enhancement of equation-of-state and conductivity for multi-species systems
   - Available tools (beams, diagnostics) may be insensitive to the desired degree of manipulation

A Proposed Roadmap

- Commensurate with commonalities in “concept design” phase of AAC Research Roadmap for different accelerator schemes



2020 2021 2022 2023 2024 2025

Community-Driven MHD Code Development

3D development and validation

Improve boundaries, equation-of-state, non-LTE

Develop API, document, user-traning

Integration of MHD Software with Community Tools

PIC and fluid plasma simulations

Beamline tracking integration

Demonstrate start-to-end simulations

Experimental Validation and Physics Guidance

Active plasma lens dynamics and control

Plasma diagnostic studies (afterglow, ionization)

High repetiton-rate sources (capillary waveguides)

Conclusion: MHD Modeling Enhances Structured Plasmas for Accelerators

- Structured plasmas enable next generation accelerators to address ABP Grand Challenges

- The development and integration of MHD codes with traditional computational tools is essential to supporting the design of future plasma-based accelerator systems

- These tools, and the devices they support, are synergistic to several other SC offices
  - Longitudinal phase-space manipulation is critical for FEL operation (BES)
  - Active plasma lenses can augment traditional focusing elements (HEP/NP/BES)
  - Gas systems are effective attenuators for x-ray FELs (BES)
  - Laser deposition and plasma evolution are critical for HEDP (FES)
  - Non-destructive diagnostics support all programs

- Significant contemporary efforts to study tools, with some modeling support
  - LBNL is pre-eminent facility in US for capillary studies, complemented by DESY in Europe
  - Worldwide FACET-II collaborative studies for PWFA target shaping, beam manipulation, and diagnostics
  - Additional efforts for MHD modeling at BNL ATF, UCLA, Imperial College, and elsewhere for ion acceleration
  - HEDP community emphasis, with significant efforts at University of Rochester and LLNL