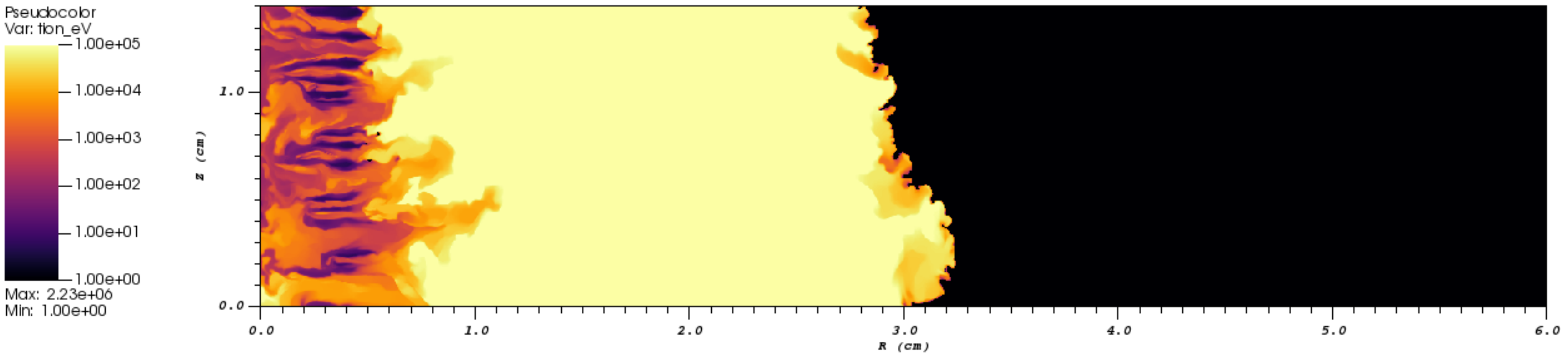
Modeling the CESZAR Gas-Puff Z-Pinch in the Radiation Magnetohydrodynamics FLASH code



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APS DPP 2022
Spokane, WA
2022-10-21

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This material is based upon work supported by the U.S. Department of Energy (DOE), National Nuclear Security Administration under Award Numbers DE-NA0003842, DE-NA0003856, and DE-NA0004031, and under Subcontracts No. 536203 and 630138 with Los Alamos National Laboratory, and Subcontract No. B632670 with Lawrence Livermore National Laboratory. We also acknowledge support from the U.S. DOE Advanced Research Projects Agency-Energy (ARPA-E) under Award Number DE-AR0001272.

Introduction

- **Gas Puff Z-Pinches** are attractive as a source of intense x rays/neutrons and their potential for nuclear fusion energy.
  - **CESZAR** uses a linear transformer driver that achieves **0.5-MA current** and <200-ns rise times without pulse compression, demonstrating high energy-coupling efficiency to the load.
  - The high shot rate possible on CESZAR make it an ideal platform for **parameter scans** and **benchmarking** of numerical simulations.

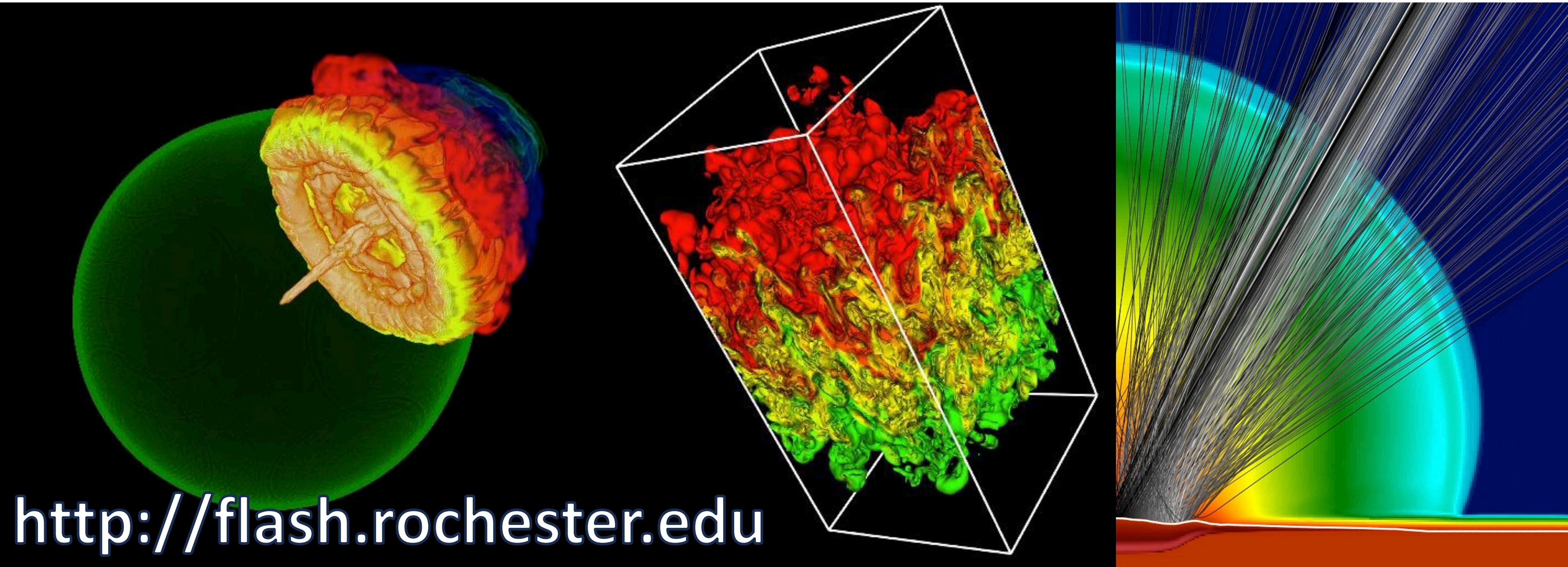
- *Ab initio* full-system simulations of these experiments are critical for their successful **design, execution, and interpretation**.
  - Several Z-pinch-capable MHD codes are of limited access to the academics performing Z-pinch experiments.
  - The Flash Center for Computational Science at the University of Rochester is developing FLASH, which has become the premier simulation code for the academic HEDP and Lab Astro communities.

The FLASH code

- FLASH (Fryxell et al. 2000) is a publicly available, high-performance computing (HPC), adaptive mesh refinement (AMR), finite-volume, hydro and MHD code with extended physics capabilities (Tzeferacos et al. 2015). Supported primarily by the U.S. DOE NNSA, LANL, LLNL, and LLE.
- FLASH is professionally managed software in continuous development for 20 years: coding standards; version control; daily automated regression testing; extensive documentation; user support; integration of extensive code contributions from external users.

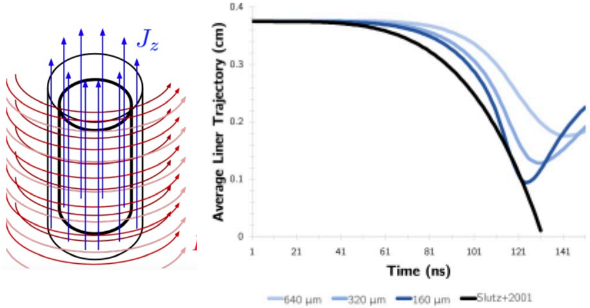
> 4,000 users world wide

>1,300 papers published with FLASH



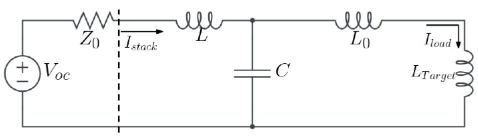
FLASH has well-developed MHD capabilities for Z-pinches

- Current Drive Unit (**M.B.P. Adams**)
  - Current I(t) is specified from file or analytically.
  - Magnetic Field $\mathbf{B}_\phi$ set on domain boundary.



M.B.P. Adams, 2020-10-08, *Implementing Z-Pinch dynamics in the FLASH code*

- Circuit Model Unit (**K. Moczulski**)
  - I(t) solved self-consistently with driver circuit.
  - Potential calculated from magnetic flux $\mathbf{\Phi}_B$.



$$\begin{pmatrix} \frac{V_c^{new} - V_c^{old}}{dt} \\ \frac{I_{stack}^{new} - I_{stack}^{old}}{dt} \\ \frac{I_{load}^{new} - I_{load}^{old}}{dt} \end{pmatrix} = \begin{pmatrix} \frac{I_{stack}^{new} - I_{load}^{new}}{C} \\ \frac{-V_c^{new} - Z_o I_{stack}^{new} + V_{oc}}{L} \\ \frac{V_c^{new} - V_t}{L_o} \end{pmatrix}$$

K. Moczulski, APS DPP 2021, *Implementation and verification of LC circuit for Z-pinch FLASH Simulations*

- Extended MHD (**E. Hansen et al.**)
  - Anisotropic magnetic resistivity, etc.
  - Magnetic resistivity solved *implicitly*.

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{\mathbf{J}}{n_e e} \times \mathbf{B} - \frac{\nabla P_e}{n_e e} + \frac{\eta_{\|}}{\epsilon_0 \omega_{pe}^2 \tau_{ei}} \mathbf{b}(\mathbf{b} \cdot \mathbf{J}) + \frac{\eta_{\perp}}{\epsilon_0 \omega_{pe}^2 \tau_{ei}} \mathbf{b} \times (\mathbf{J} \times \mathbf{b}) - \frac{\eta_{\wedge}}{\epsilon_0 \omega_{pe}^2 \tau_{ei}} (\mathbf{b} \times \mathbf{J})$$

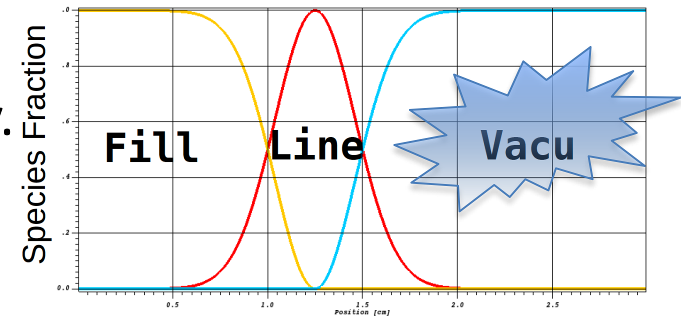
E. Hansen, APS DPP 2021, *Extended Magnetohydrodynamics in the FLASH code*

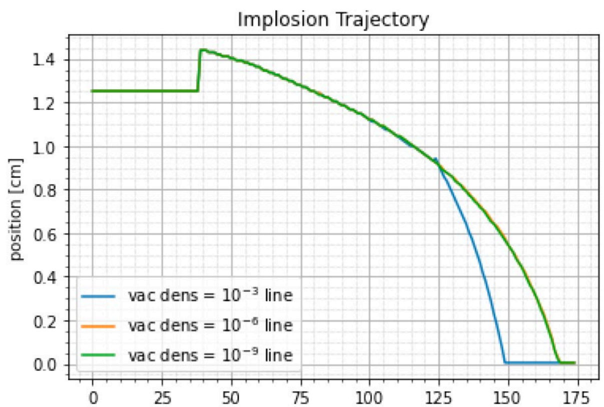
One-dimensional FLASH Z-pinch simulation

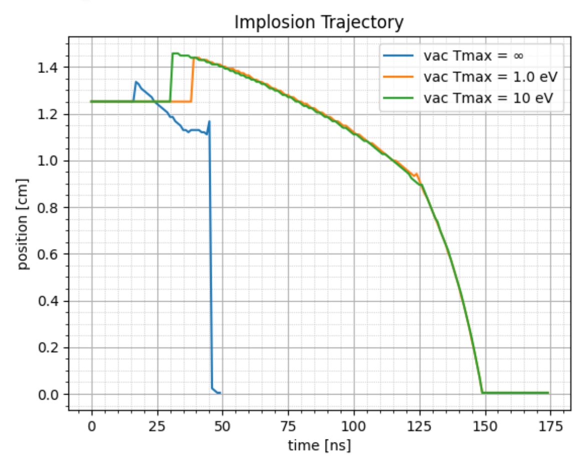
One- vs. Two- dimensional FLASH simulations

Pseudo-Vacuum physics requires explicit treatment

- Vacuum must be low-density and high-resistivity.
  - Density initialized to $< \sim 10^{-6}$ of liner.
  - Resistivity forced to $\sim 10^{14}$ cm^2/sec.
- Cannot have spurious heating of vacuum.
  - Temperature ceiling set to $\sim$1 eV.
  - Ohmic heating disabled.

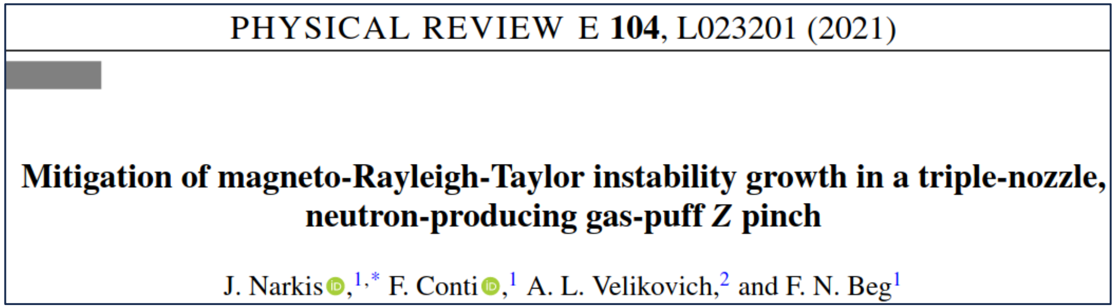






CESZAR experiment for FLASH and HYDRA comparison

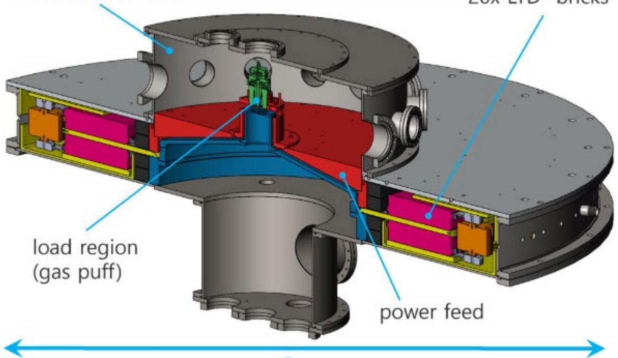
- CESZAR experiments use multiple gas puffs and axial magnetic field.



PHYSICAL REVIEW E **104**, L023201 (2021)

Mitigation of magneto-Rayleigh-Taylor instability growth in a triple-nozzle, neutron-producing gas-puff *Z* pinch

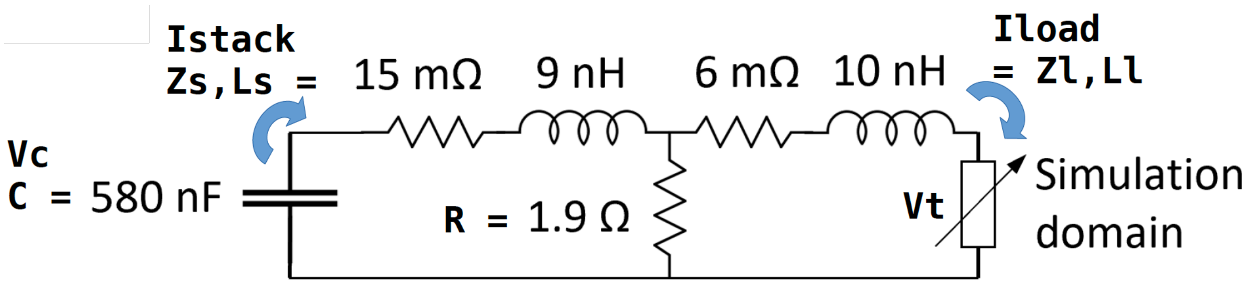
J. Narkis,[1,*] F. Conti,[1] A. L. Velikovich,[2] and F. N. Beg[1]



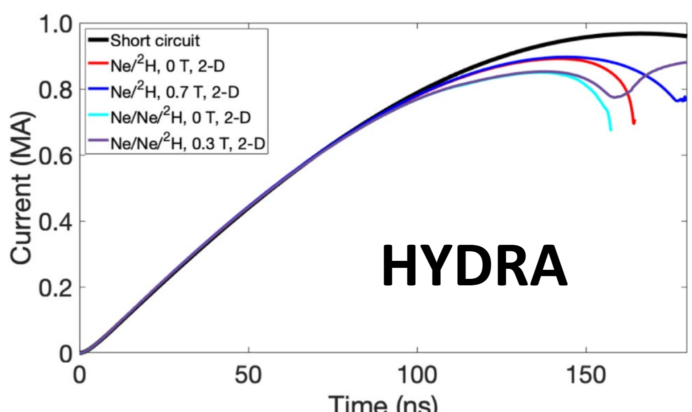
- Published HYDRA results give density profile and MRTI growth rate.
  - FLASH will compare single and dual liner runs, with no axial field.

The CESZAR Circuit Model is implemented in FLASH

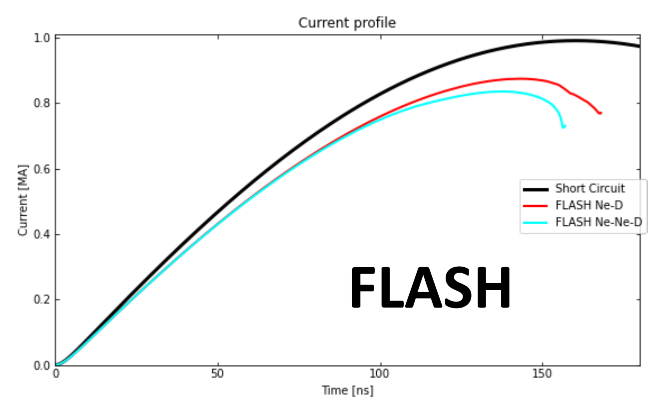
- The CESZAR circuit model is solved in FLASH.
  - For verification, the static load current is solved with a Python script.



- Published HYDRA currents I(t) are compared to FLASH and Python solvers.
  - Despite static load calculations differing, simulated currents agree well.



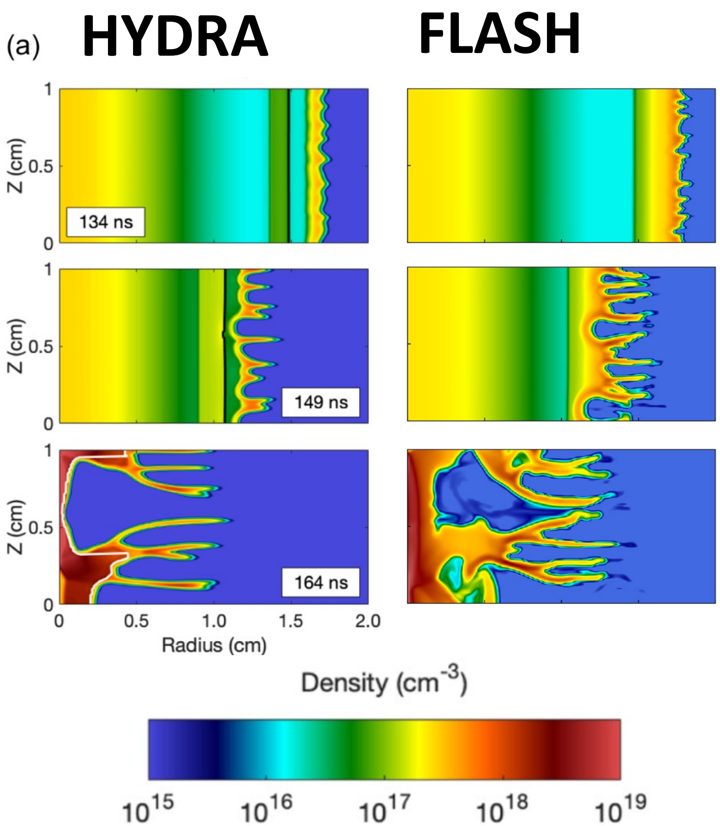
Narkis et al. 2021 Fig. 1



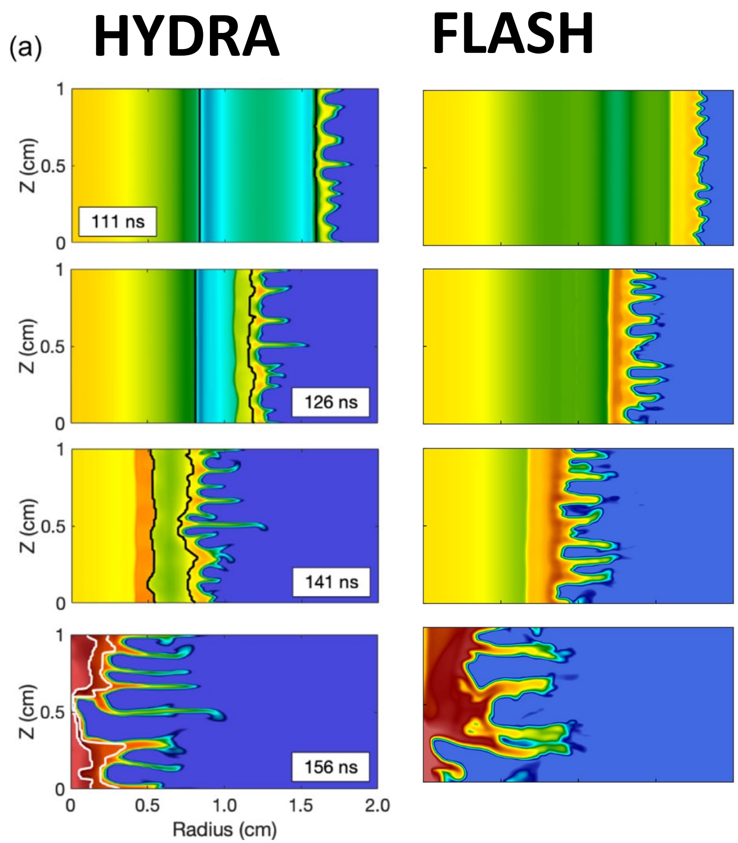
Density evolution is comparable to HYDRA

- The 2-D density profiles are plotted at 3 or 4 different times.
  - Implosion trajectories agree well, and profiles are qualitatively similar.

Single liner



Dual liner

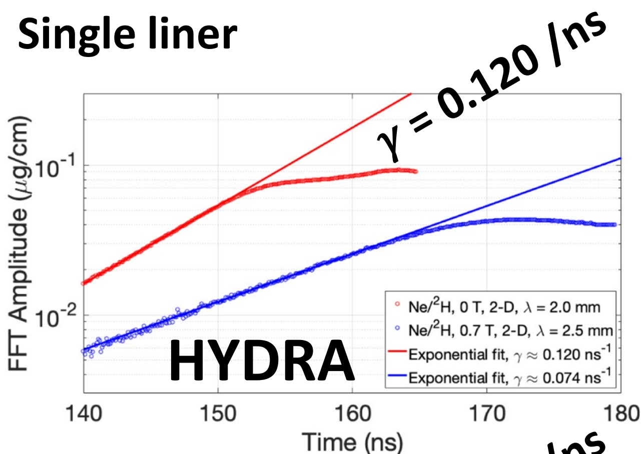


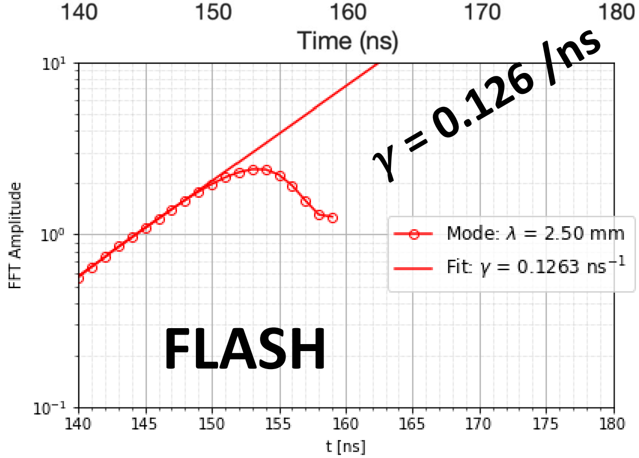
Narkis et al. 2021 Fig. 3, 5

MRTI growth rates agree with HYDRA and theory

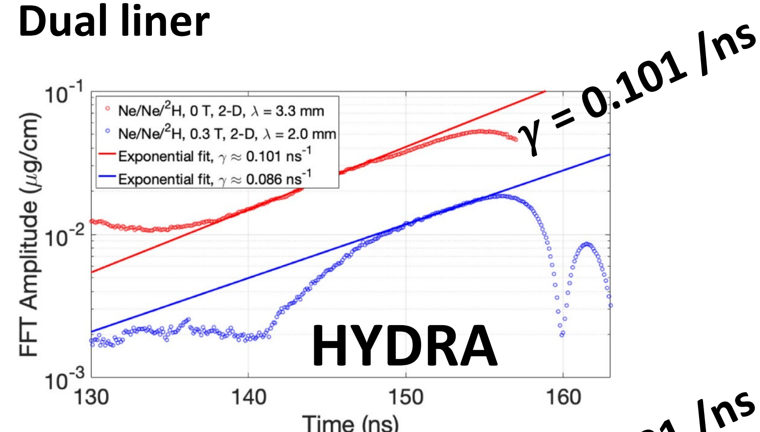
- Density is integrated radially, and Fourier transformed in z, to ρ (k_z).
  - Exponential growth fit of dominant-mode amplitudes agree very well.

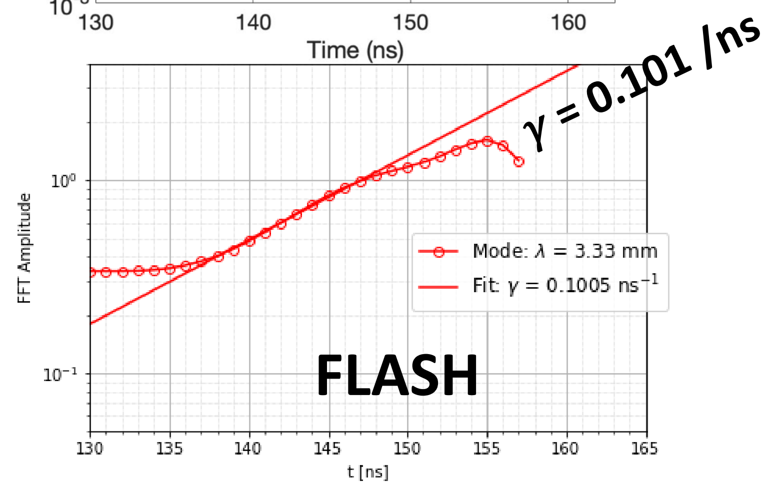
Single liner





Dual liner





Narkis et al. 2021 Fig. 4, 6

Summary

- The CESZAR gas-puff Z-pinch demonstrates **high energy-coupling efficiency** to the load and high repetition rate, making it an ideal platform for **parameter scans and benchmarking numerical simulations**.

- FLASH has well-developed **Z-pinch simulation capabilities**, including current drive, circuit models, extended MHD terms, and implicit magnetic resistivity.

- FLASH simulations of CESZAR experiments compared very favorably with published HYDRA results, demonstrating that **FLASH can robustly model gas-puff Z-pinches**.

Two-dimensional FLASH Z-pinch simulation