Numerical study of the magnetic field influence on sub-nanosecond laser-foam interaction

J. Löffelmann[1], O. Klimo[1,2]

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[1]Czech Technical University, Prague, Czech Republic; [2]ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Dolni Brezany, Czech Republic

Introduction

This work investigates the influence of **self-generated** and **externally applied** magnetic fields on foam homogenization. The goal is to provide fundamental insights for upcoming experiments to be conducted at the Prague Asterix Laser System (PALS) facility [1].

A new type of low-density foam target is used in our experiments. The foam consists of tightly packed SiO_2 hollow spheres with an average density of *15-40 mg/cc*.

The main motivation for using this foam is its ability to generate long-length-scale plasma for efficient measurement of **parametric instabilities** (SBS, SRS, TPD) under plasma conditions relevant to ICF. In future experiments, the influence of an external magnetic field on parametric instabilities will be studied.

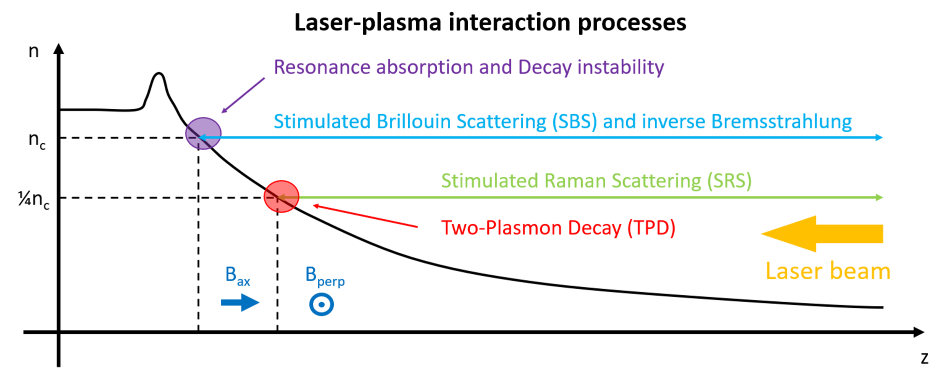
We investigate magnetic field transport during the laser-foam interaction. Due to high laser intensity, the plasma conditions reach a **non-local regime**. Strong electron temperature gradients in the plasma corona lead to magnetic field generation via the **Biermann effect** and to magnetic field advection through the **Nernst effect**. These effects play a dominant role in influencing the macroscopic magnetic field strength and transport. In the non-local regime, however, these terms can be overestimated in the extended MHD model [2].

An **improved limiter** for the heat-flux and thermoelectric terms is proposed, and different models for **anomalous resistivity** are examined.

Simulations are performed using the **FLASH code** [3].

Simulation and experimental setup

- Foam targets with spheres of different diameters – **variable average density**
- Laser beam setup: $E = 200\ J$, 3ω (438 nm), $50\ \mu m$ focal radius (Gaussian)
- Models used:
  - Radiation hydrodynamics
  - Extended magnetohydrodynamics (extended MHD):
    - **Nernst effect** (magnetic field advection)
    - **Anisotropic** thermal conductivity $\boldsymbol{\kappa}$ and magnetic resistivity $\boldsymbol{\eta}$
    - **Biermann battery** and **Seebeck effect** (self-generated magnetic fields)
    - Hall effect, Cross-field Nernst and Righi-Leduc not included in the simulations
  - FEOS EoS, TOPS opacity tables
  - Cylindrical or Cartesian geometry, laser energy deposition (inverse Bremsstrahlung)



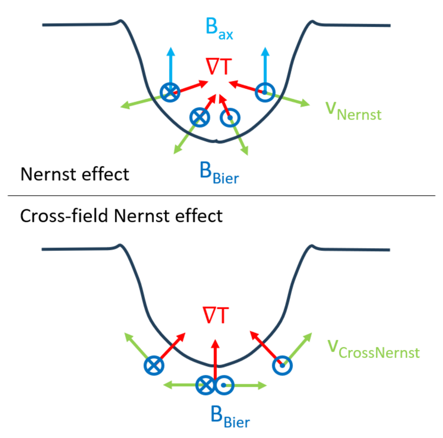
Iodine photodissociation laser at PALS

Fundamental wavelength:	*1315 nm*
Laser pulse FWHM:	*200-350 ps*
Energy on target:	*up to 700 J*
Laser intensity:	*~3×10¹⁶ W/cm²*
Focus diameter:	*~50-200 μm*

- External magnetic field applied in parallel (axial) or perpendicular direction to laser beam propagation
- Study the influence of an external magnetic field on parametric instabilities and laser-plasma dynamics
  - **Enhanced SBS** backscattering [4]
  - Possible **non-axial part of SRS and TPD inhibition** due to an axial magnetic field [5]
  - Thermal conduction inhibition
- Magnetic field transport under strong temperature gradients
  - **Field cavitation** and **compression** due to thermoelectric effects [6]

Magnetic field transport in non-local laser plasma

- Strong Nernst advection transports the magnetic field from the hot plasma to the ablation zone behind the critical surface
- Higher magnetization in low-density foam leads to radial magnetic field advection from the shock front (Cross-field Nernst effect)
- External axial magnetic field cavitation and compression behind the critical surface, not advected by Cross-field Nernst at the shock front
- Heat flux needs to be limited in the MHD model due to large temperature gradients



- Typical flux limiter based on **free-streaming limit**

$$q_{FS} = f_{FL} v_e n_e T_e, \qquad |\mathbf{q_{FL}}| = \frac{1}{\frac{1}{q_{FL}} + \frac{1}{|\boldsymbol{\kappa}\nabla T_e|}}$$

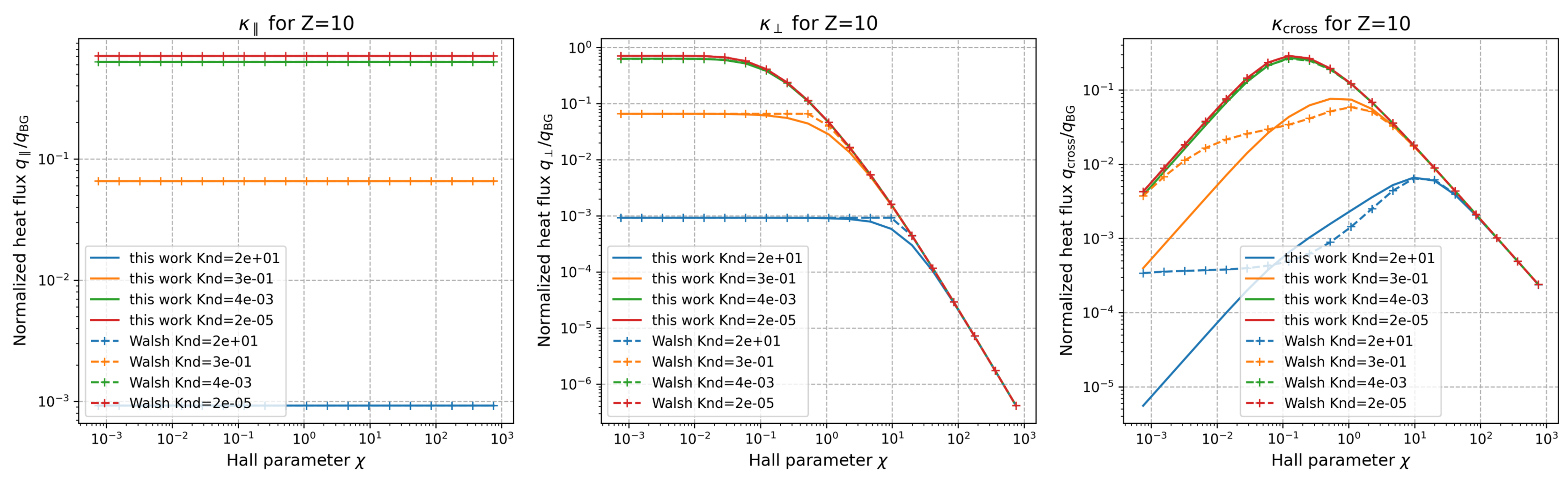
- Problems:
  - Fixed constant α, no dependence on average ionization
  - Strong magnetization χ (Hall parameter) increases locality – not captured
- Solution:
  - A new form of heat flux limiter based on VFP simulations [7]
  - Non-locality parameter: $\lambda_d = \sqrt{(Z^2 + 0.24Z)/(Z + 4.2)}\lambda_{ei}$, $K_{nd} = \lambda_d / L_T$
  - Limiter for Biermann battery – non-local suppression of $\boldsymbol{B}$ generation [8]
  - Limiter for thermal electric terms – paired version [7] keeps fractions $\kappa_\parallel/\gamma_\parallel$, $\kappa_\perp/\gamma_\perp$ and $\kappa_\wedge/\gamma_\wedge$ **constant**
  - This work uses modified limiters – better scaling of $\kappa_\wedge$ for small magnetization [9]

This work:

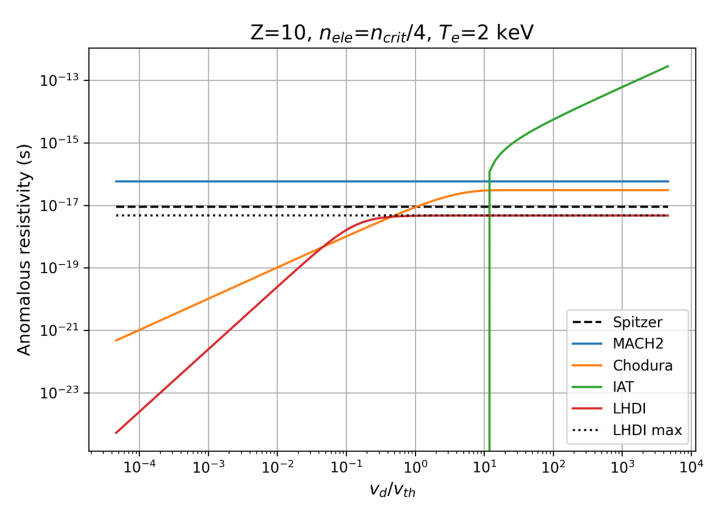
$$q_\parallel = -\frac{\kappa_\parallel \nabla_\parallel T_e}{1 + \frac{\lambda_d}{f_{new} L_{T_\parallel}}}$$

$$q_\perp = -\frac{\kappa_\perp \nabla_\perp T_e}{1 + \frac{\lambda_d}{f_{new} L_{T_\perp}} \frac{\kappa_\perp^c}{\kappa_\parallel^c}}$$

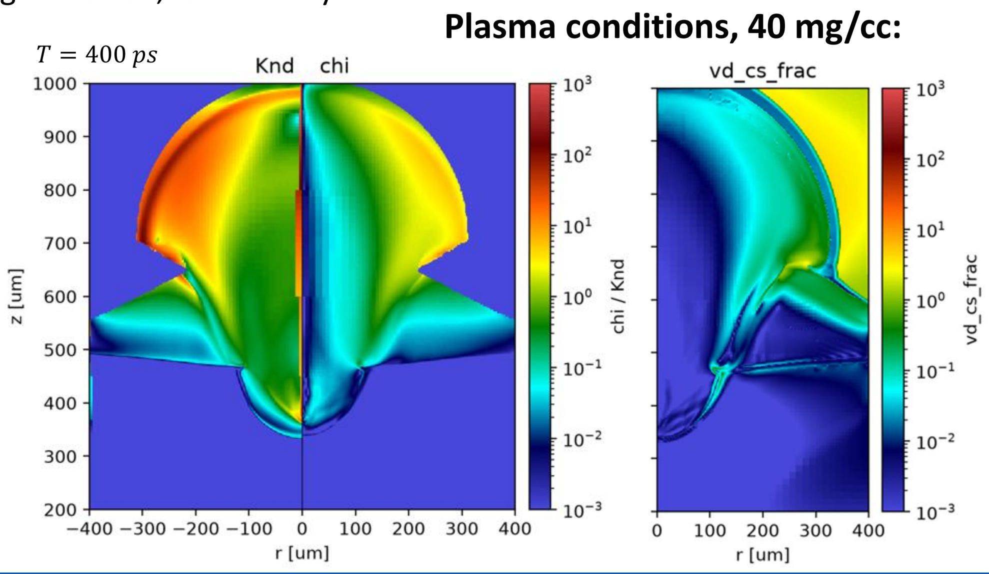
$$q_\wedge = -\frac{\kappa_\wedge \nabla_\wedge T_e}{1 + \frac{\lambda_d}{f_{new} L_{T_\perp}} \frac{\kappa_\perp^c}{\kappa_\parallel^c}}$$



- Classical extended MHD model uses collisional resistivity $\eta_{Spitzer} \sim T_e^{-3/2}$ (with anisotropic coefficients)
- The considered plasma is heated and rapidly expands; large angular magnetic field is generated via Biermann
- Strong currents $\boldsymbol{j} = \nabla \times \boldsymbol{B}$ break down the fluid approximation when the electron drift velocity surpasses the kinetic threshold → $v_d = |\mathbf{j}|/(en_e) \gtrsim v_i$ or c_s, this leads to anomalous resistivity (scattering on small-scale $\boldsymbol{E}$ wave fluctuations) → micro-instabilities:
- **Ion-Acoustic Turbulence** (IAT) – low magnetization, $T_e \gg T_i$, low density
- **Lower-Hybrid Drift Instability** (LHDI) – strong magnetization, low density

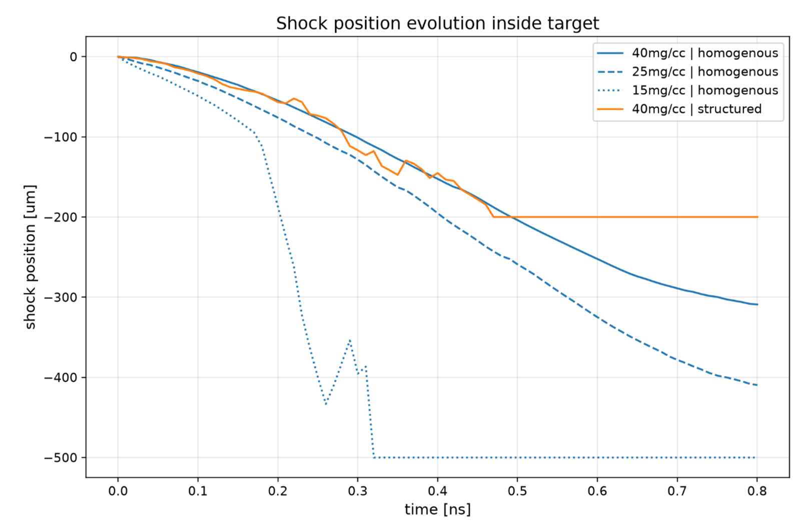


Plasma conditions, 40 mg/cc:



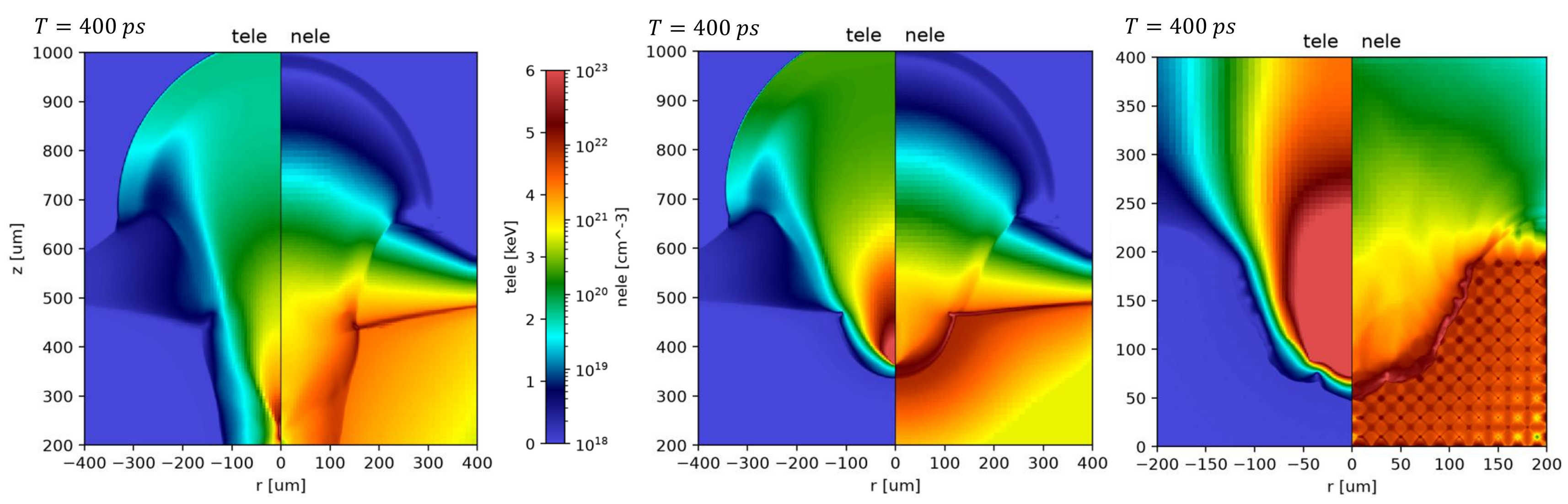
Foam homogenization in external magnetic field

- Shock velocity and laser penetration into the foam target are measured by x-ray streak camera in experiments
- We locate the shock position (depth inside the target) in the extended MHD simulation in the central area of the beam
- There is a clear **dependence of shock velocity on foam density**
- For the subcritical density *15 mg/cc* ($\rho_c \approx 19.3\ mg/cc$ for 3ω), the simulation shows a **significant jump in shock velocity** at around *180 ps*
- Laser beam penetrates the foam rapidly – 2D density and temperature profiles

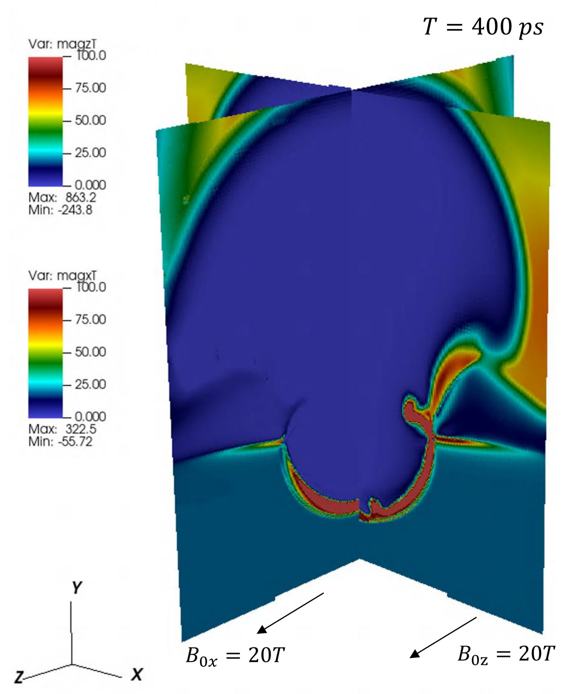


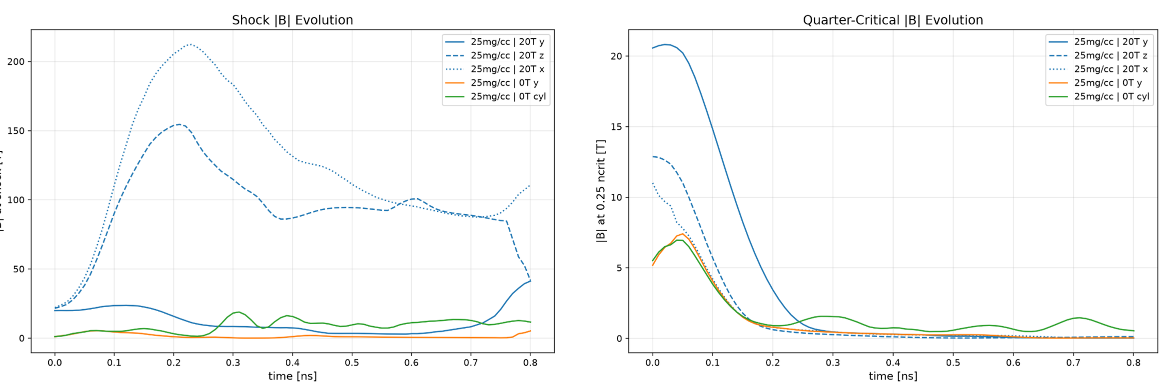
- Shock velocity result from a homogeneous target in the simulation follows the experimental measurement for 3ω
- Highly resolved simulation of foam structure shows agreement with the homogeneous target simulation
- Experimental measurement for 1ω deviates from the simulation → possibility of laser beam scattering on the hollow spheres and increased absorption (volume heating) that is not captured by the ray tracing algorithm in the FLASH code

15 mg/cc, homogen. **40 mg/cc, homogen.** **40 mg/cc, structured**



- We perform 2D cartesian simulations to examine the influence of different orientations of the initial external magnetic field on homogenization and plasma dynamics
- Two cases: $\mathbf{B} \parallel laser$, $\mathbf{B} \perp laser$ (in 2D, this can be either parallel or perpendicular to the simulation domain)
- In all simulations, external and self-generated magnetic fields are strongly advected from the interaction region via the Nernst effect; at *200 ps*, effectively no magnetic field persists in the heated plasma (for all cases $B_0 = 0,1,10,20$ T)
  - The exception is the 2D cartesian simulation with parallel field remaining till *250 ps*
- The magnetic field is advected to the shock front and in the radial direction
  - In both cases of $\mathbf{B} \perp laser$, the **very strong magnetic field** (*100-200 T*) is **accumulated** at the shock front compared to the $\mathbf{B} \parallel laser$ case, where both Biermann and external fields are advected away radially
  - Magnetic field parallel to the computation domain is pushed from the plasma corona, while the perpendicular field is accumulated at the beam edge
  - Although there is no significant difference in shock velocities





Conclusions

- Simulations of non-local laser plasma conditions using the extended MHD model are difficult – **magnetothermal instability** (Nernst + Righi-Leduc), limiting of ∇T_e terms (Biermann, heat flux, thermoelectric terms), anomalous resistivity – hard to capture kinetic effects accurately in the macroscopic model
- Results show complex magnetic transport can influence shock velocity at subcritical foam densities, leading to fast homogenization
- Improved scaling of anomalous resistivity and Ohm heating fraction (both ion and electron heating through resistivity) is necessary to capture kinetic effects
- A more accurate model of laser beam interaction with foam structure is needed to better resolve shock velocity and homogenization
- Structured simulation of subcritical foam density is needed to evaluate the validity of rapid homogenization

Acknowledgements

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References

[1] Jungwirth, K., et al.: Physics of Plasmas 8 (2001)

[2] Sherlock, M. and Bissell, J. J.: Physical Review Letters (2020)

[3] The Flash Center for Computational Science. https://flash.rochester.edu

[4] Yao, W., et al.: Physical Review Letters 130 (2023)

[5] Zhang, Y., et al.: High Power Laser Science and Engineering 12 (2024)

[6] Walsh, C.A. , et al.: Nuclear Fusion 61 (2021)

[7] Walsh, C.A. and Sherlock, M.: Physics of Plasmas (2024)

[8] Davies, J. R.: Physics of Plasmas (2023)

[9] Arran, C., et al.: Physics of Plasmas (2025)