Toward Advanced Modeling of Transport in Magnetized Inertial Confinement Fusion Targets

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Summary

- Over the course of the past summer, preliminary work has been done to investigate transport in magnetized ICF systems using both electrostatic PIC simulations and MHD simulations
- A 1-D MHD code has been written from the ground up to explore the simulation of magnetized, cylindrical ICF systems
  - this code was written using the results of Velikovich, Giuliani, and Zalesak as a foundation [1]
  - a comparison of results is given below

ICF: inertial confinement fusion
PIC: particle-in-cell
MHD: magnetohydrodynamic

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Governing Equations for MHD Simulations

Continuity equation

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nu) = 0$$

Heat-balance equation

$$3n\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x}\right) + 2nT\frac{\partial u}{\partial x}$$

$$= \frac{\partial}{\partial x}\left[\left(\kappa_\perp^{e} + \kappa_\perp^{i}\right)\frac{\partial T}{\partial x} + \frac{c\beta_\wedge^{uT}}{4\pi e n}\frac{\partial B}{\partial x}\right] + \frac{1}{4\pi}\frac{\partial B}{\partial x}\left(v_{m\perp}\frac{\partial B}{\partial x} + \frac{c\beta_\wedge^{uT}}{en}\frac{\partial T}{\partial x}\right)$$

Induction equation

$$\frac{\partial B}{\partial t}\frac{\partial}{\partial x}(uB) = \frac{\partial}{\partial x}\left(v_{m\perp}\frac{\partial B}{\partial x} + \frac{c\beta_\wedge^{uT}}{en}\frac{\partial T}{\partial x}\right)$$

Constant-pressure condition (subsonic compression limit)

$$\frac{\partial}{\partial x}\left(2nT + \frac{B^2}{8\pi}\right) = 0$$

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Abstract

The effects of externally applied magnetic fields on the performance of fusion targets has been an open topic of research since the inception of ICF and is still a topic in which our understanding can be greatly improved. Previous work has suggested that for high-gain 1-D targets, improved burn characteristics from magnetization are offset by the impediment of burn-wave propagation for little net improvement. Similar studies have shown that the application of axially aligned fields to cylindrical targets may lower the required areal density for ignition, but detailed analysis of burn-wave propagation in magnetized cylindrical targets has not been performed, aside from a cursory look using fluid models relying on Braginskii transport coefficients. Over the course of the past summer, using the results of a paper by Velikovich *et al.* [1] as a foundation, work has been done to explore simulation of magnetized cylindrical ICF systems with 1-D magnetohydrodynamics using the results of a study by Basko *et al.* [2] with 2-D particle-in-cell methods. Following this, initial work has been done on the development of a magnetized smoothed particle hydrodynamics model of similar systems.

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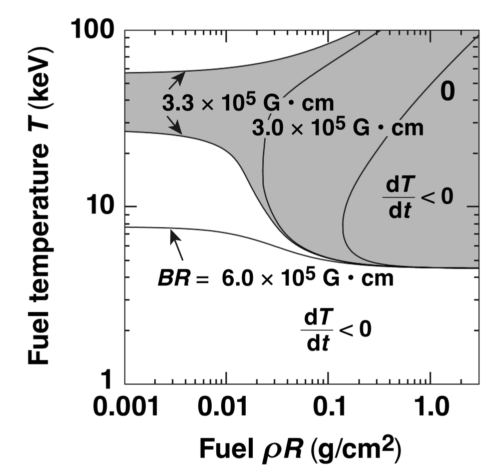
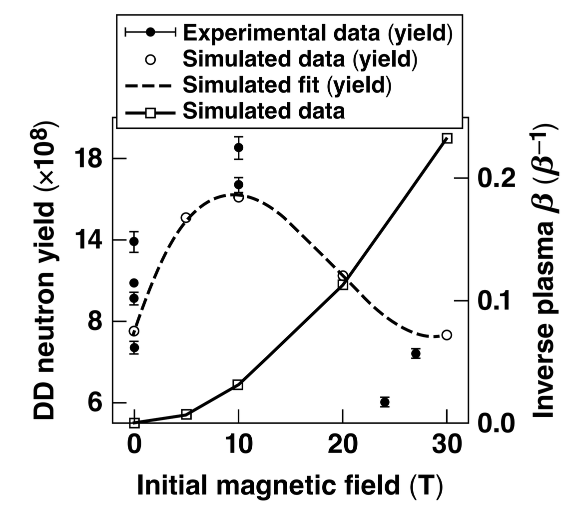
Motivation

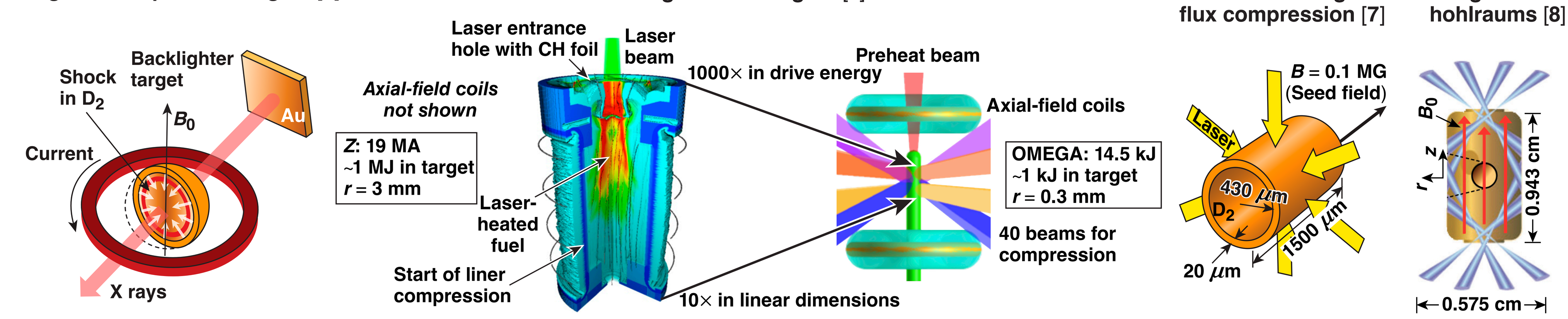
- In the presence of magnetic fields, ignition conditions are modified to reduce areal density requirements (figure adapted from [2])





- For MagLIF-type systems, while yield is improved by the presence of an axial field, high field strengths can limit maximum yield [3] (figure adapted from [4])
- This effect may have already been seen in mini-MagLIF experiments [4]

- A multitude of magnetized fusion-related experiments have been of recent interest (figures adapted from associated references)



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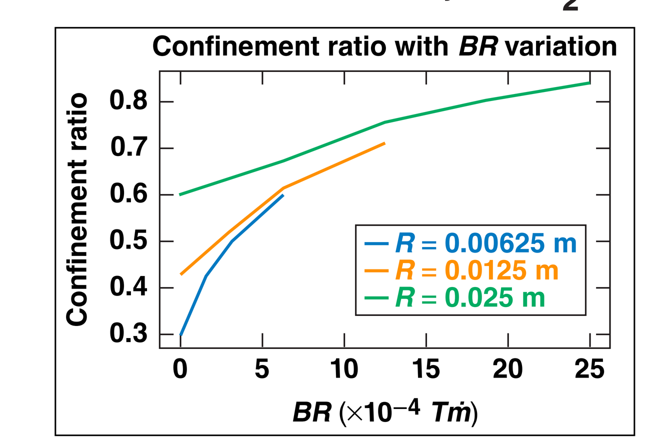
MagLIF: magnetized liner inertial fusion

2-D Electrostatic PIC Simulations

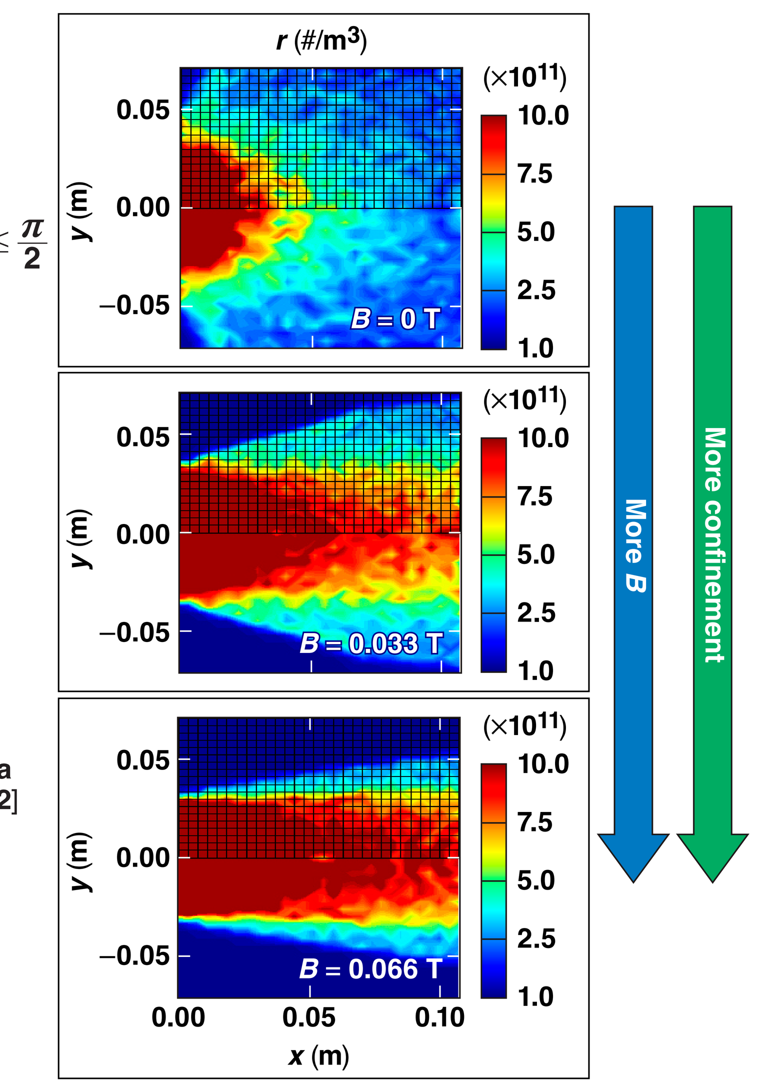
- Particles are accelerated at each step using the Boris push
- The electric potential/field is calculated at each step using a modified Gauss–Seidel method
- Injection energy is thermally broadened
- The initial direction chosen randomly from $-\frac{\pi}{2} \le \theta \le \frac{\pi}{2}$



- In the case of a magnetized system, the ICF ignition criterion Eq. (5) for areal density (ρR) is replaced by a corresponding criterion for the quantity (BR) Eq. (6) [2]

$$\begin{cases} T = 5-7\ \text{keV} \\ \rho R \ge 0.2\ \text{g/cm}^2 \end{cases} \qquad (5)$$

$$\begin{cases} T = 5-7\ \text{keV} \\ BR \ge (4.5-6.5)10^5\ \text{G cm} \end{cases} \qquad (6)$$



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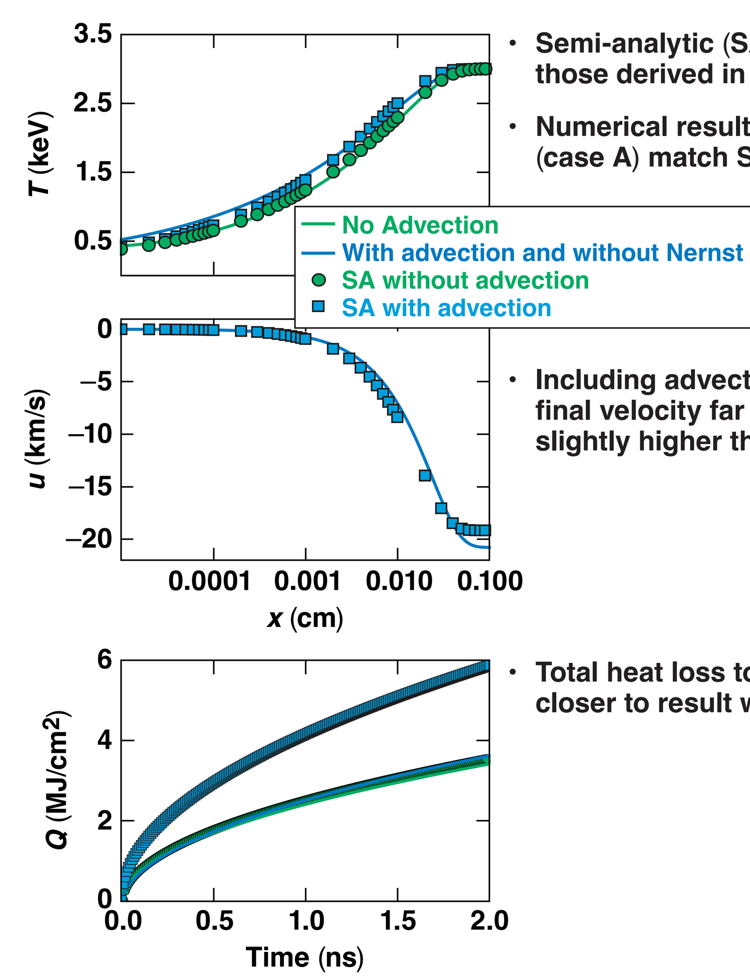
1-D MHD Simulations

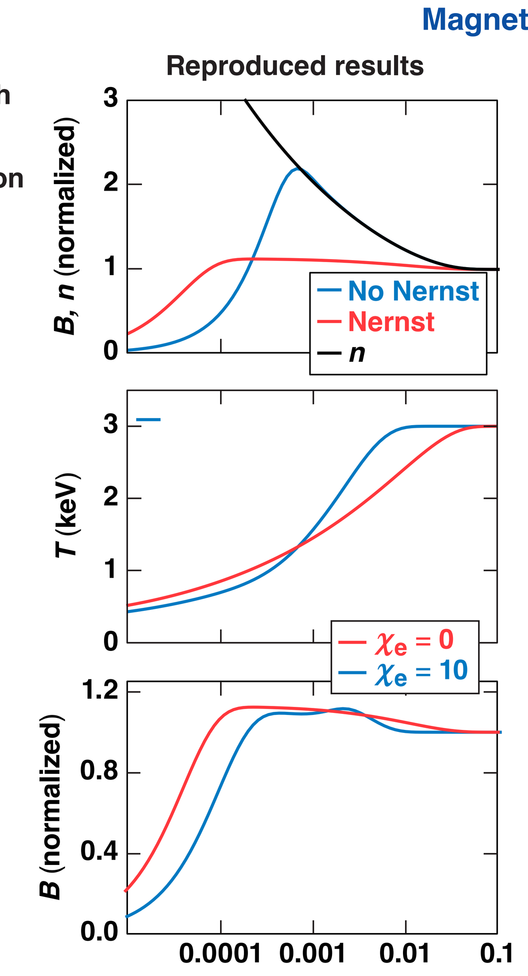
Unmagnetized results

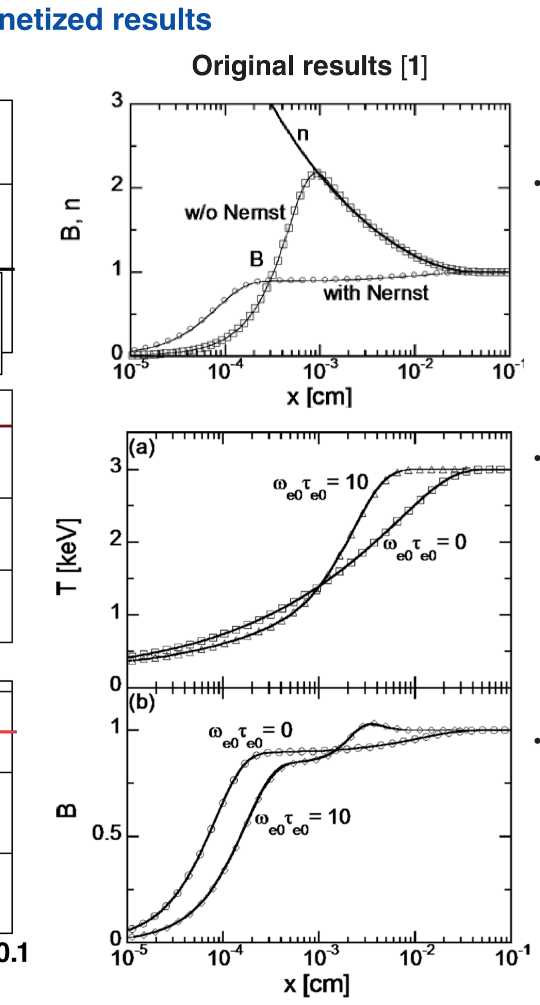


- Semi-analytic (SA) solutions match those derived in [1]
- Numerical results without advection (case A) match SA solutions well
- Including advection (case B), final velocity far from wall is slightly higher than SA result
- Total heat loss to boundary closer to result without advection

Unmagnetized parameters					
Case	$B\ (x = 0)$	$B\ (x = \infty)$	$T\ (x = 0)$	$T\ (x = \infty)$	χ_e
A/B	0 G	1 G	0.3 keV	3 keV	5×10^{-7}

Magnetized results





- Results including resistive terms but not thermoelectric terms (case C), match well
- Some difference in the final value of the magnetic field at the wall when thermoelectric terms are included
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Looking to the future: TriForce

- TriForce is an open-source multiphysics code for hybrid fluid-kinetic simulations
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References

[1] A. L. Velikovich, J. L. Giuliani, and S. T. Zalesak, AIP Conf. Proc. 1639, 59 (2014).
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Acknowledgements

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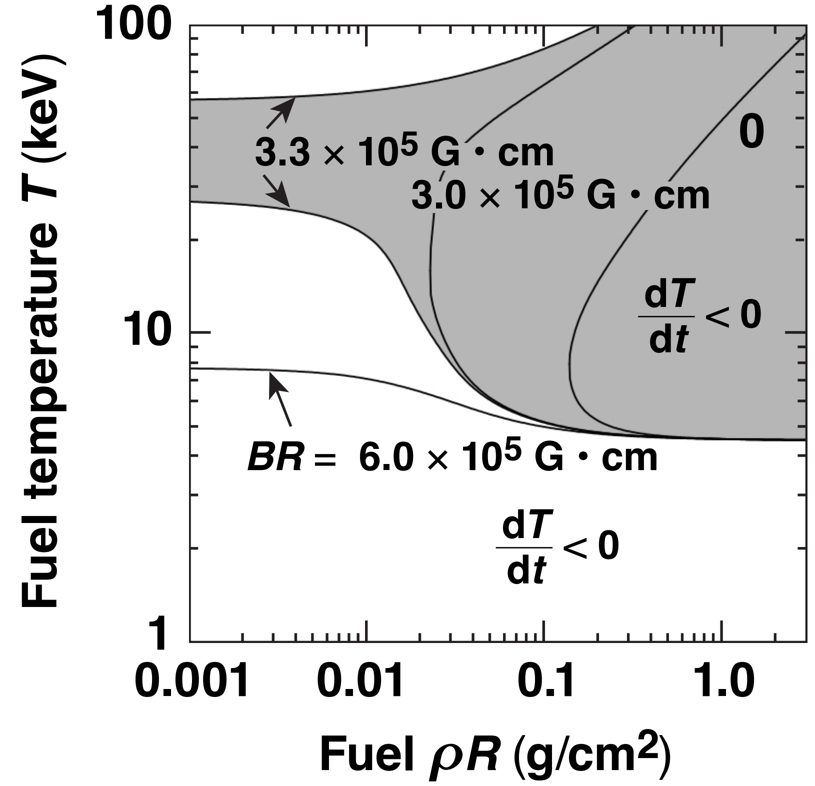

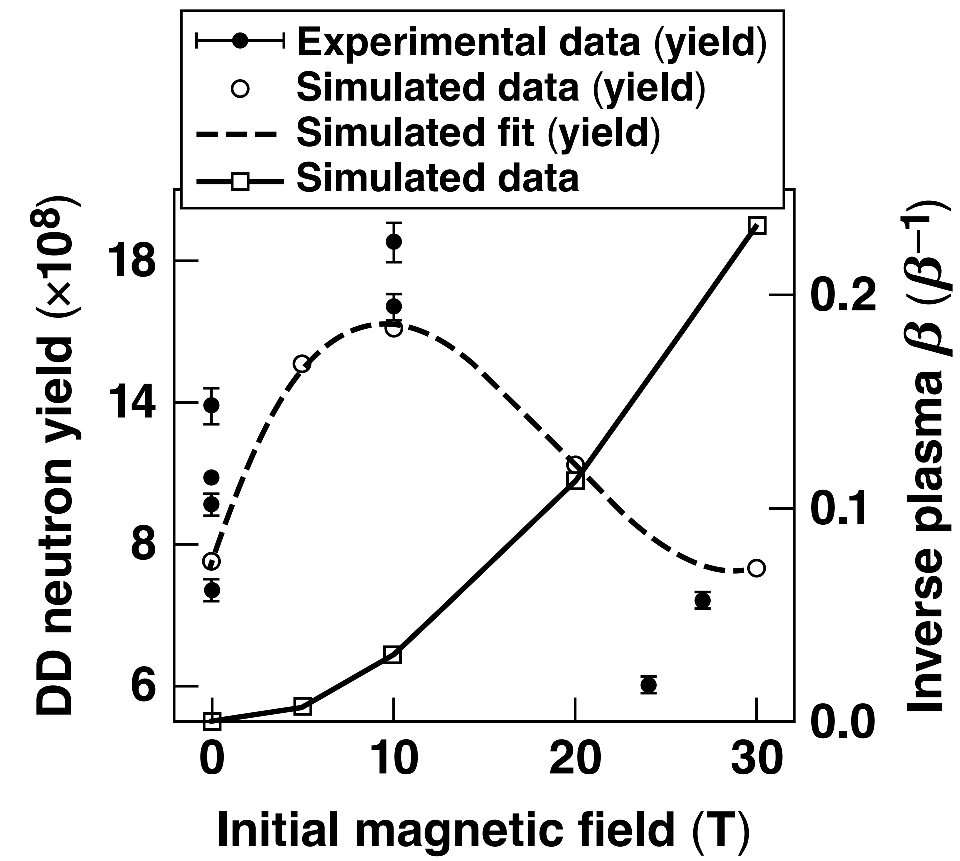

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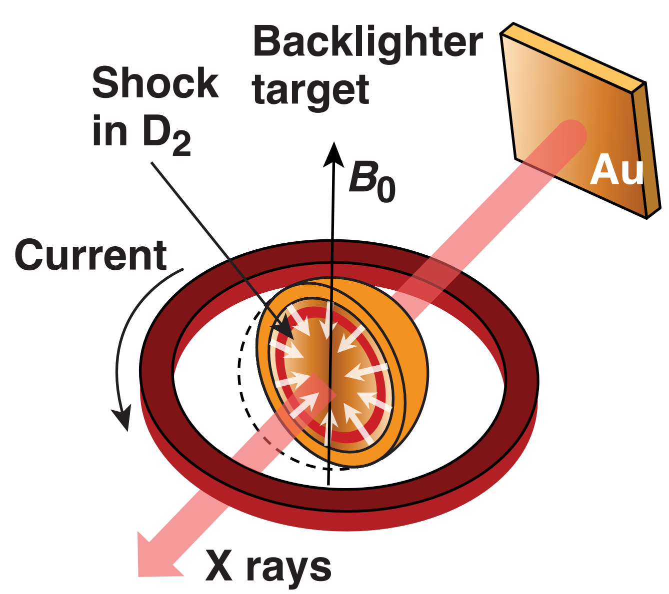
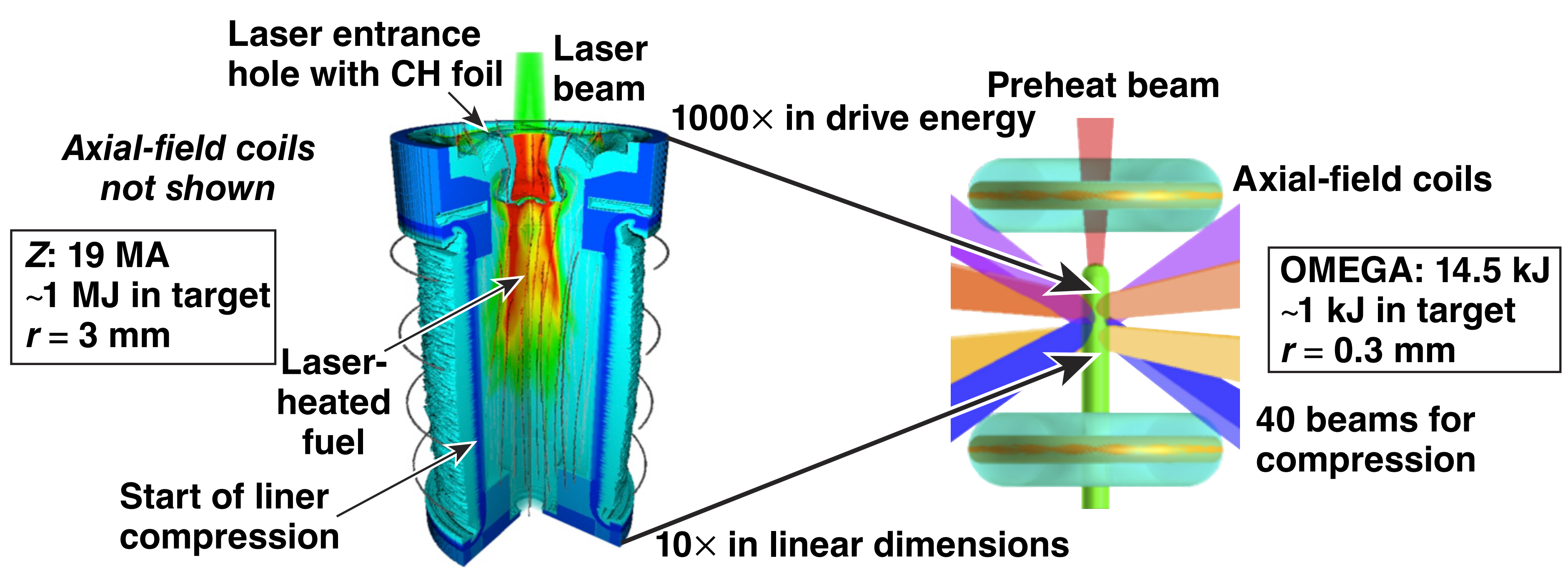
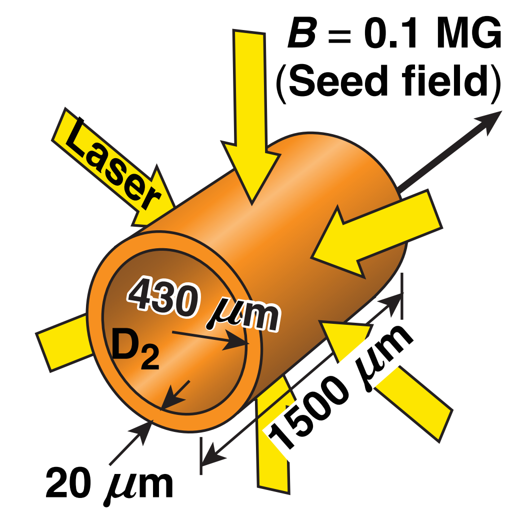


MagLIF/Mini-MagLIF [6]



Laser-driven magnetic flux compression [7]



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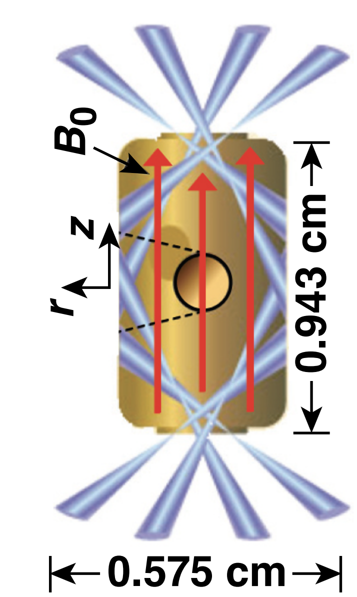

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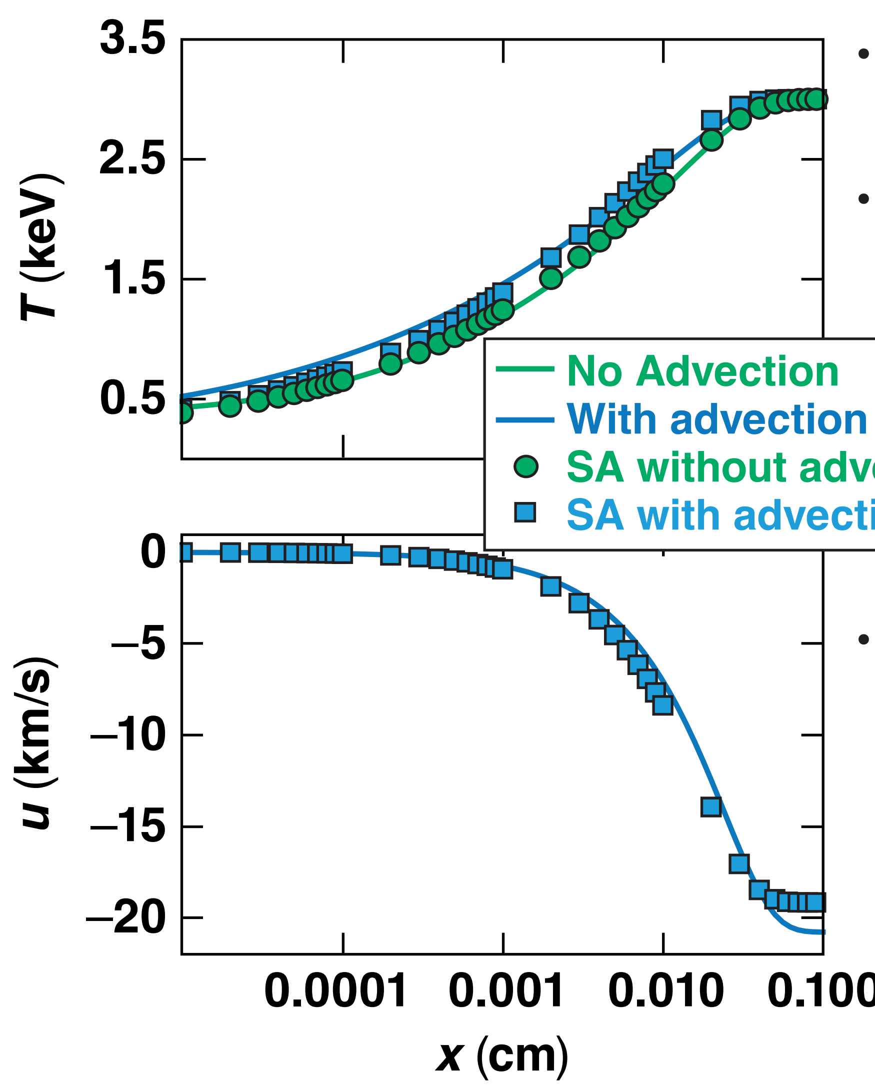

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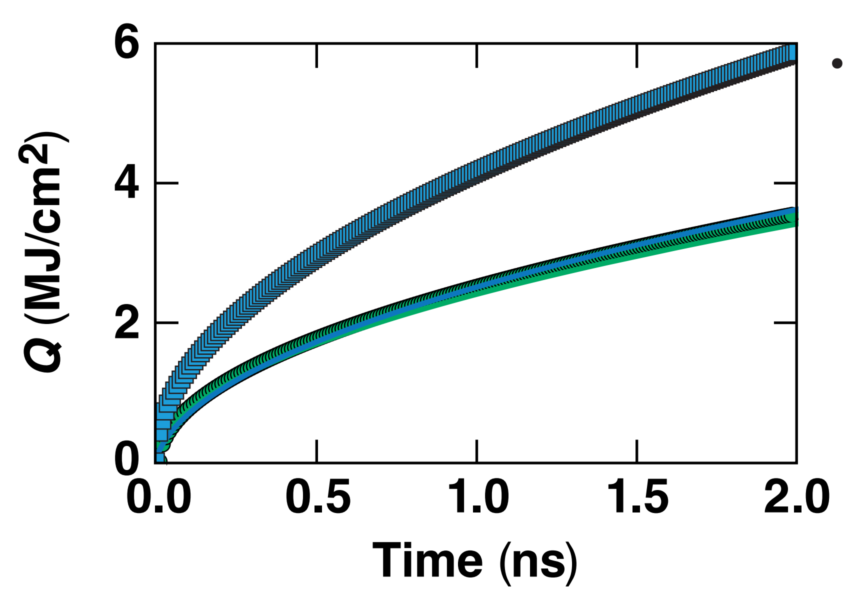

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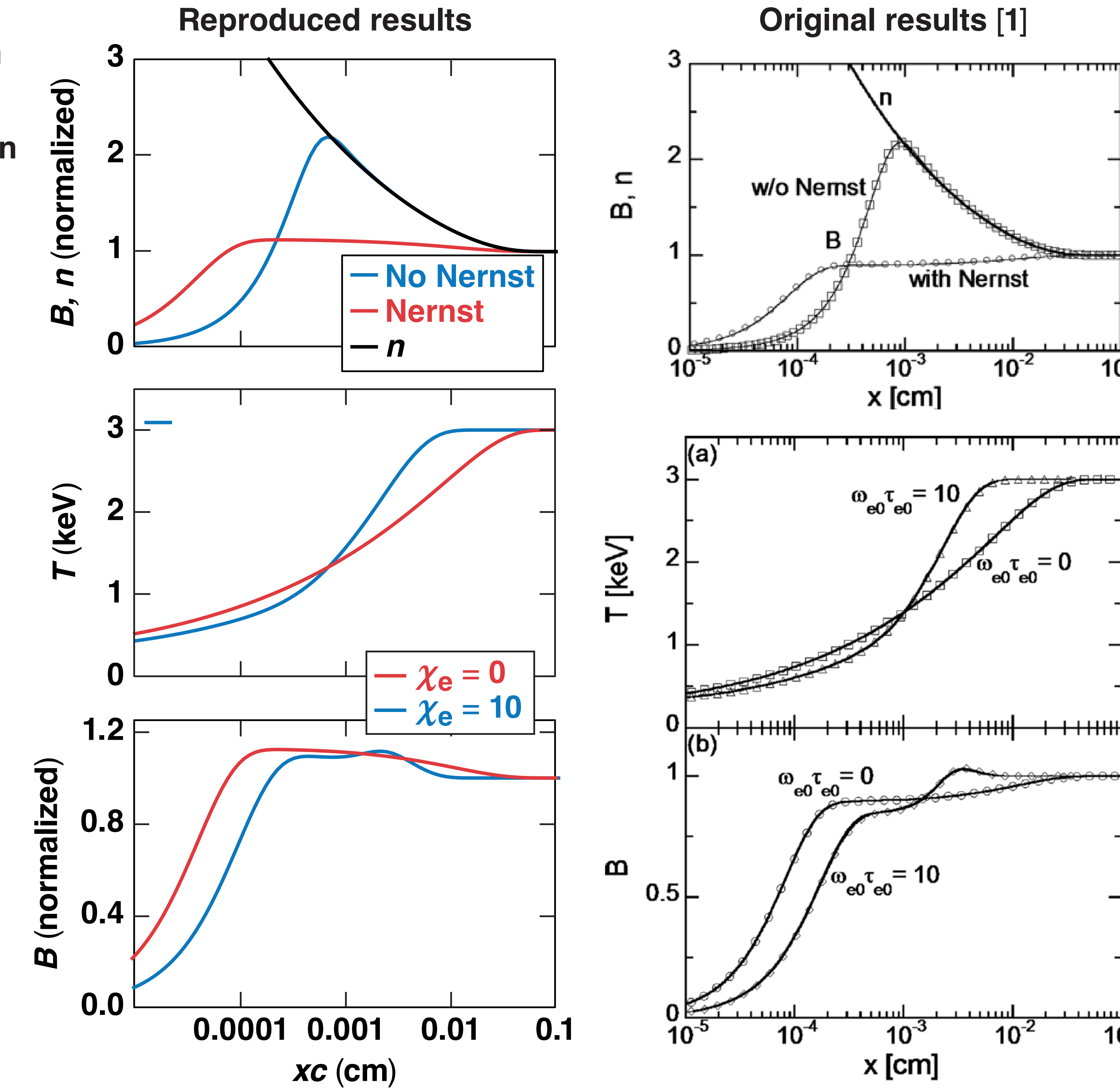

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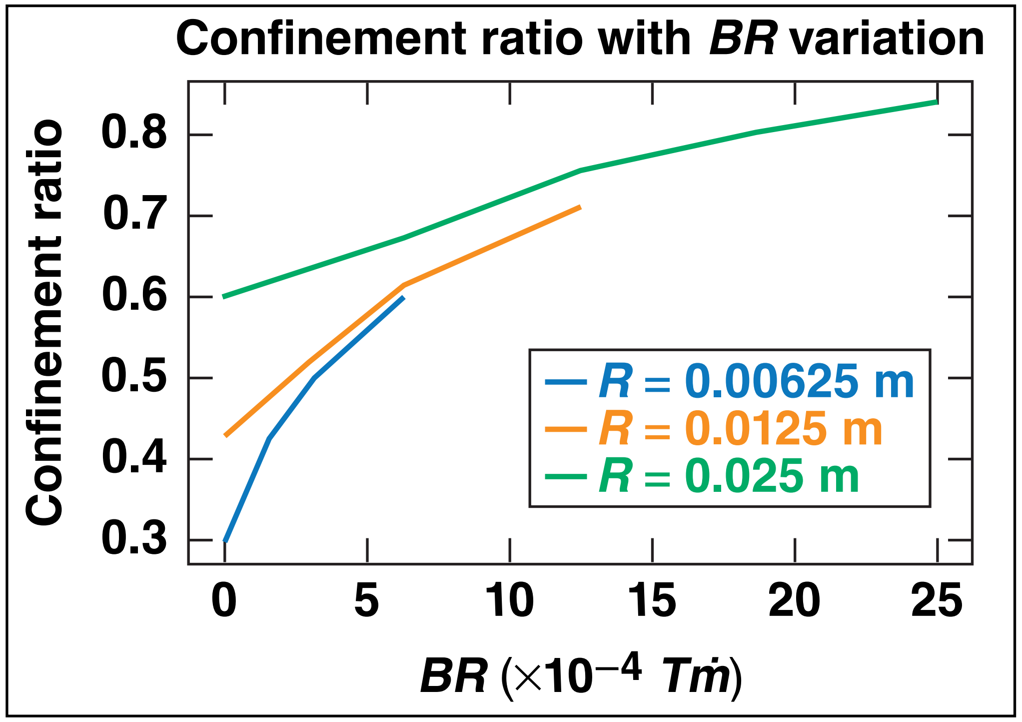

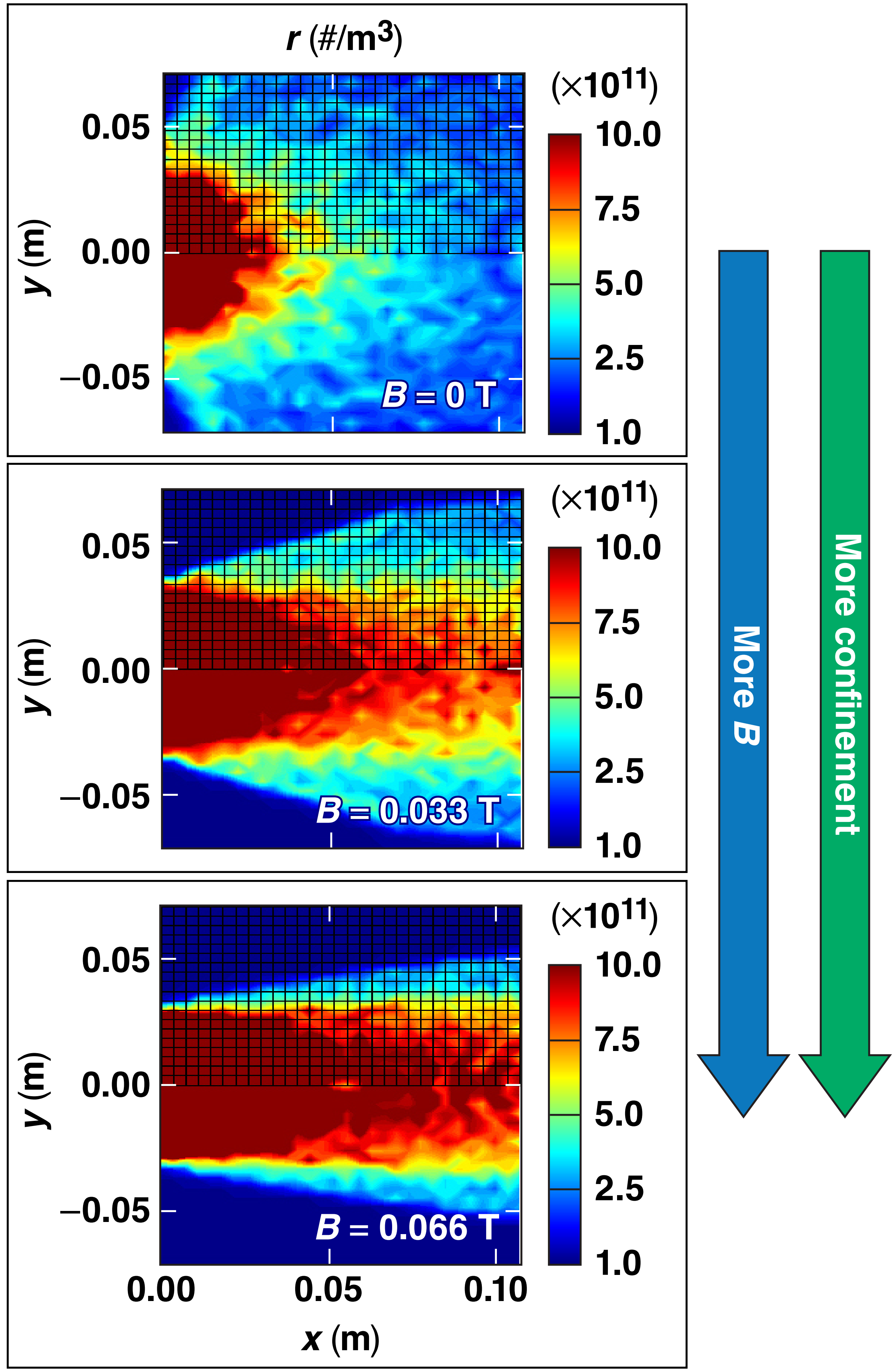

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