Relativistically Thermal Plasma Generation by Magnetically Assisted Direct Laser Acceleration

K. WEICHMAN,[1] J. P. PALASTRO,[1] A. P. L. ROBINSON,[2] and A. V. AREFIEV[3]

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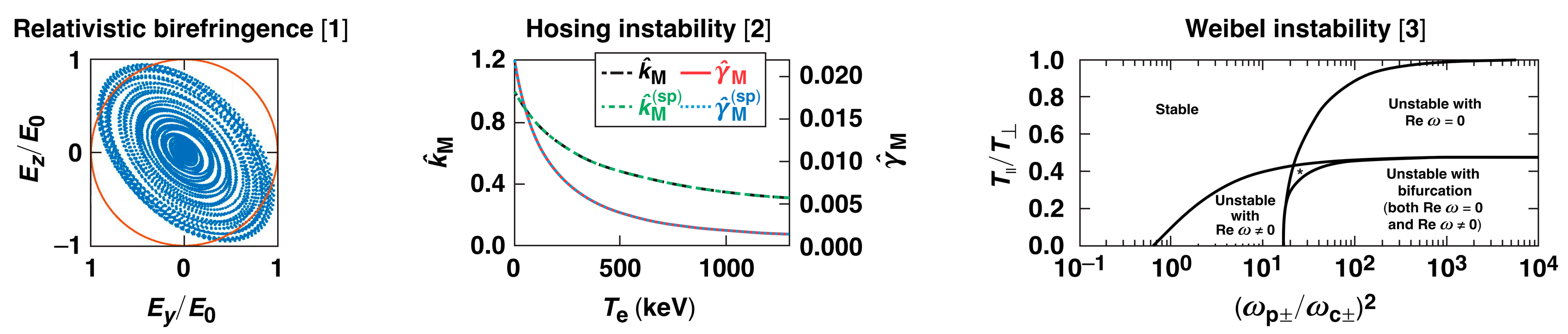
Motivation

- Relativistic electron motion significantly alters plasma dynamics, but experimental access is limited
  - non-perturbatively bulk-relativistic plasma is needed for verification of basic predictions and study of astrophysically relevant processes
  - examples
    - relativistic birefringence
    - parametric and beam-pointing instabilities
    - astrophysical shock acceleration
    - Weibel instability
  - co-occurring ultrahigh-intensity laser pulses obscure these phenomena



TC16111

Entering the non-perturbatively bulk-relativistic plasma regime requires a new type of laser-plasma heating

- Requirements
  - non-perturbatively bulk relativistic ($\gamma \gg 1$ for most electrons)
  - persistent after all driving laser pulses have passed
  - large volume
  - optically diagnosable density

Relativistically thermal plasma

Plasma-heating mechanisms	Heats majority of electrons in interaction volume?	Scalable to large volume?	Lasts after laser pulse?	Optically diagnosable?
Direct laser acceleration (DLA) in vacuum	Yes	Yes	No (reversible)	N/A
Near-critical plasma	Yes	No (propagation unstable)	Maybe (surrounded by cold dense plasma)	Maybe (requires higher-frequency probe)
Structured target	Yes	Yes	No (surrounded by cold dense plasma)	No (structure blocks diagnostic access)
Laser wakefield acceleration (LWFA)	No (hot tail)	Maybe	No (electrons escape)	Yes
Stochastic DLA (e.g., SM-LWFA)	Maybe (requires large spot and long pulse)	Maybe (long pulse unstable)	Maybe (electrons escape)	Yes
Magnetically assisted DLA	Yes	Yes	Yes	Yes

TC16112

SM-LWFA: self-modulated laser wakefield acceleration

Transverse magnetic fields break the usual DLA invariants, enabling energy retention, even in vacuum

$B = 0$

$$\frac{d}{dt}(p_y - a) = 0$$
$$\frac{d}{dt}(\gamma - p_x) = 0$$

$B \neq 0$

$$\frac{d}{d(\omega_0 t)}(p_y - a) = \frac{\omega_{c0}}{\omega_0} p_x$$
$$\frac{d}{d(\omega_0 t)}(\gamma - p_x) = \frac{\omega_{c0}}{\omega_0} p_y$$

- Regimes for energy retention, $\omega_{c0} \ll \omega_0$
  - momentum rotation is slow compared to laser cycle, but not pulse duration [4]
  - momentum rotation affects electron interaction with a single laser cycle [5]

x-propagating, *y*-polarized laser pulse with applied $B_0\hat{z}$; $\omega_{c0} = eB_0/mc$

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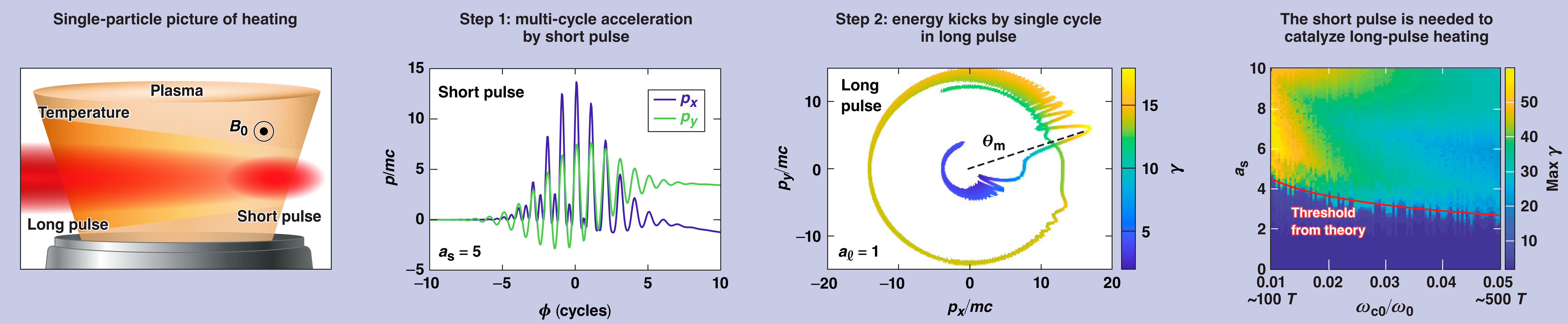
Utilizing two laser pulses couples regimes of magnetically assisted direct laser acceleration, generating relativistically thermal, underdense plasmas [6]



Particle-in-cell simulation [7]

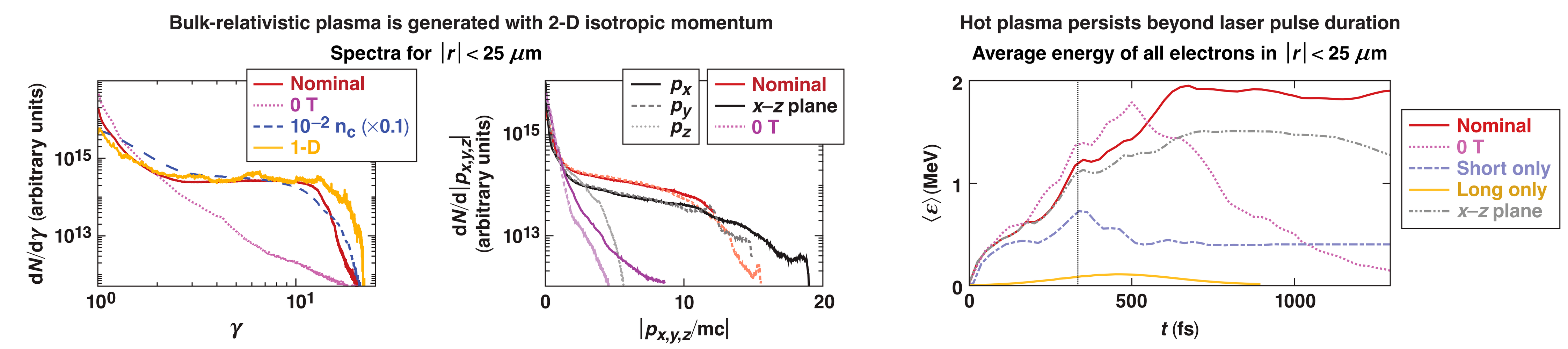
Nominal 2-D case ($x - y$)
B_0 = 500 T (in *z*)

Hydrogen; $n_e = 10^{-3}\ n_c$
L = 100 μm

Long pulse:
$a_\ell = 1$, τ_ℓ = 0.8 ps

Short pulse:
$a_s = 5$, τ_s = 20 fs

Both: 100 μm FWHM



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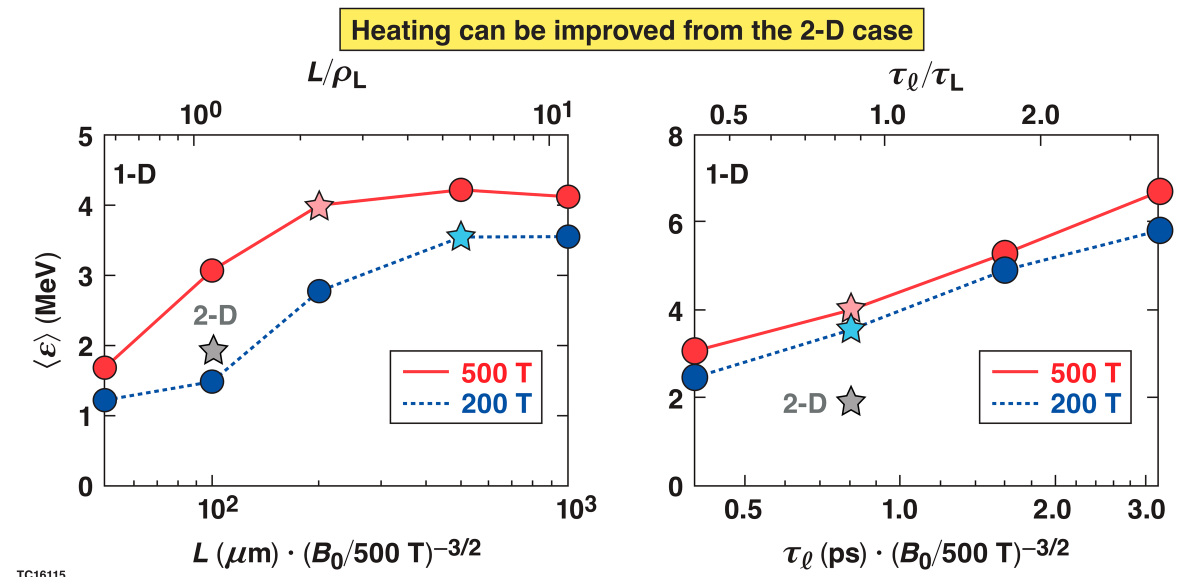
Multi-MeV plasma is predicted for a range of conditions [6,8]

Heating can be improved from the 2-D case



Theoretical scaling

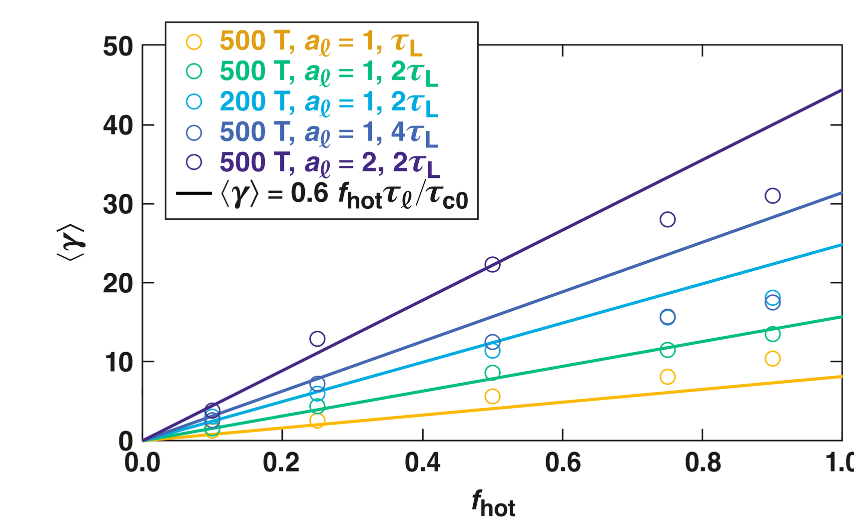
Single kick by long pulse (max):
$\Delta\gamma = 2^{3/2} a_s^{3/2} \sqrt{\omega_0/\omega_{c0}}$

Threshold for heating by long pulse:
$\gamma_0 \gtrsim 0.3 \sqrt{\omega_0/\omega_{c0}}$

Average energy if fraction of electrons above γ_0 after short pulse is f_{hot}:
$\langle\gamma\rangle \approx 0.6\ f_{hot}\ \tau_\ell/\tau_{c0}$

$\tau_L \equiv 2\pi\Delta\gamma/\omega_{c0} = \Delta\gamma\ \tau_{c0}$

$\rho_L \equiv c\tau_L/2\pi$



TC16115

Experimental verification is feasible with state-of-the-art technology

Capacitor coil magnetic field [9]/ELI Beamlines-like design

Design basis	Relevant scales	Plasma dimensions	Short pulse	Long pulse
500 T	$\rho_L \approx 40\ \mu$m	$w_0 = 50\ \mu$m	$a_s = 5$	$a_\ell = 1$
	$\tau_L \approx 0.8$ ps	$L = 200\ \mu$m	τ_s = 20 fs	τ_ℓ = 2 ps
		$n_e = 10^{18}$ cm^{-3}	ε_s = 15 J	ε_ℓ = 90 J

Pulsed-power magnetic field [10]/EP-OPAL-like design

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200 T	$\rho_L \approx$ 1 mm	$w_0 = 200\ \mu$m	$a_s = 6$	$a_\ell = 1$
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References
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[8] K. Weichman *et al.*, Phys. Plasmas 29, 053104 (2022).
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TC16116

UNIVERSITY of ROCHESTER

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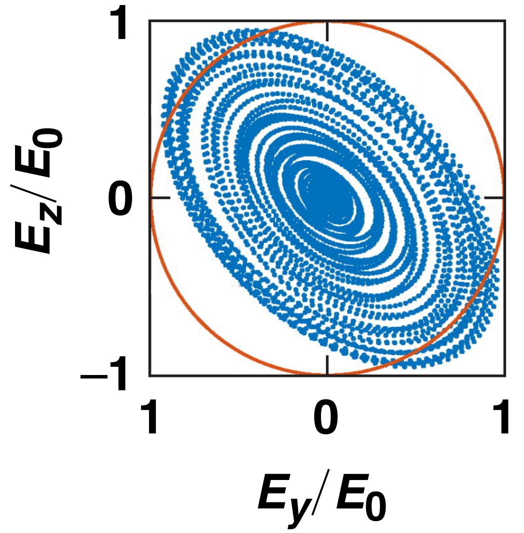
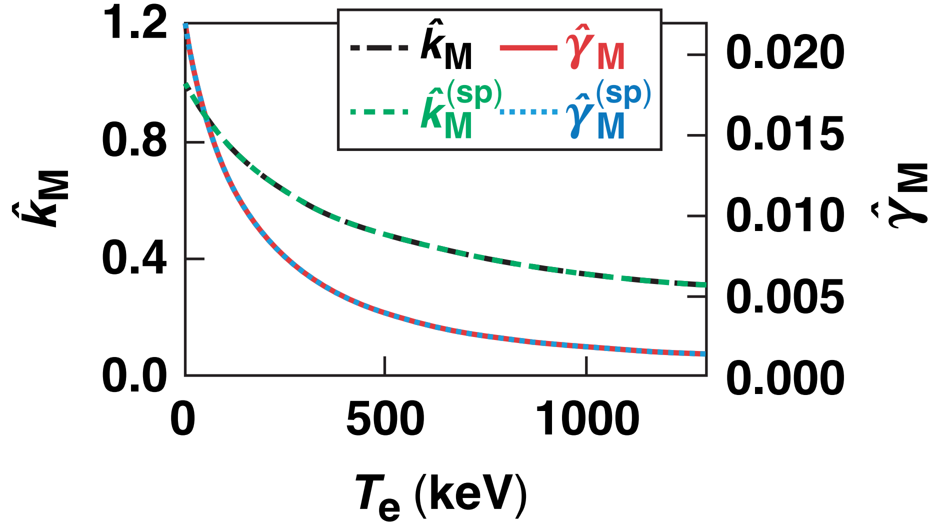
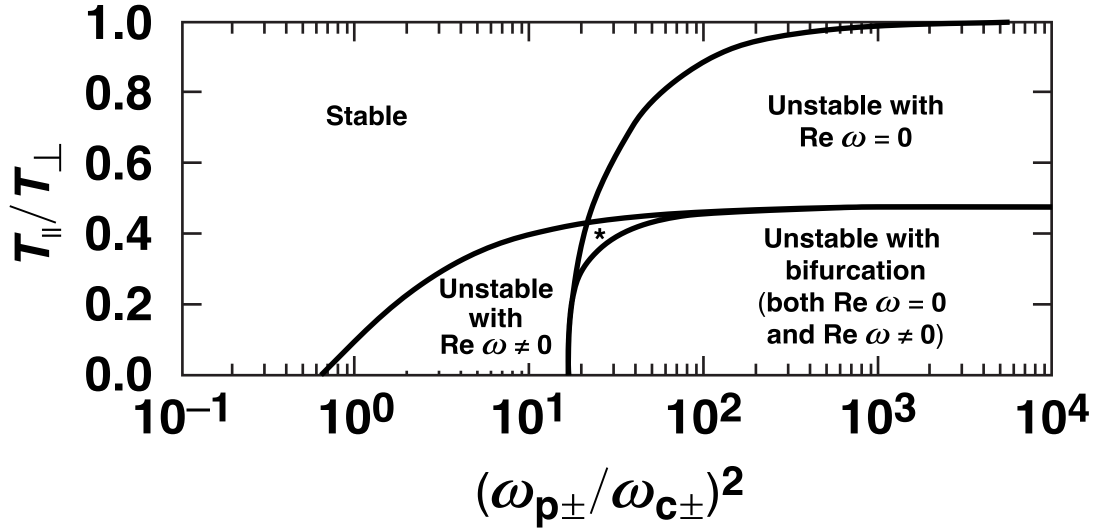
Relativistic birefringence [1]



Hosing instability [2]



Weibel instability [3]



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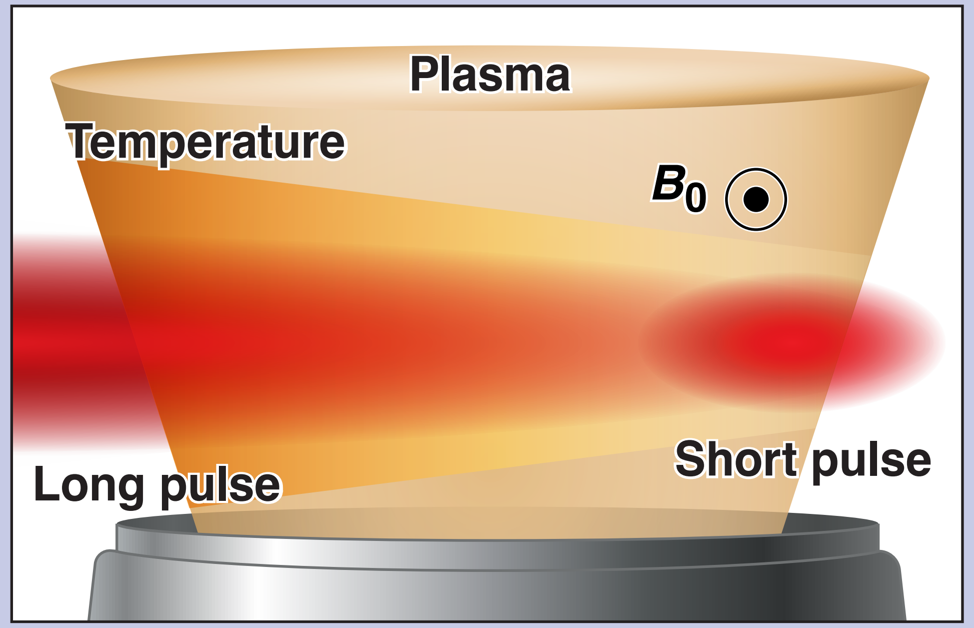
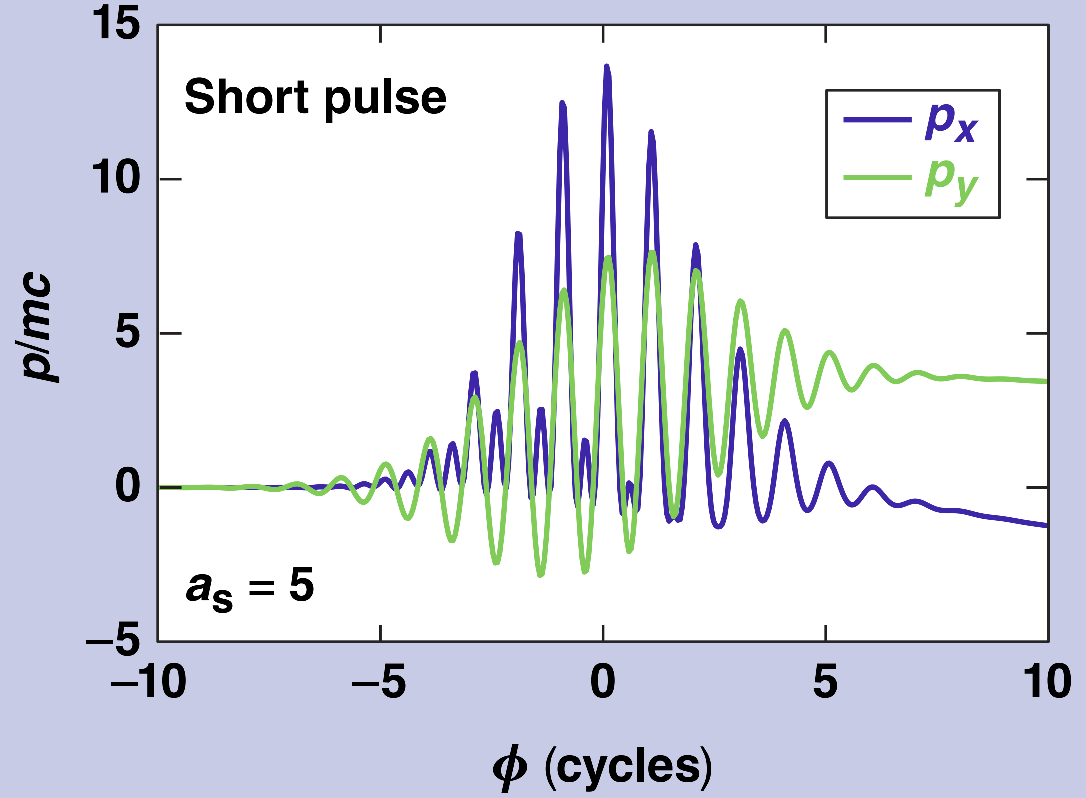
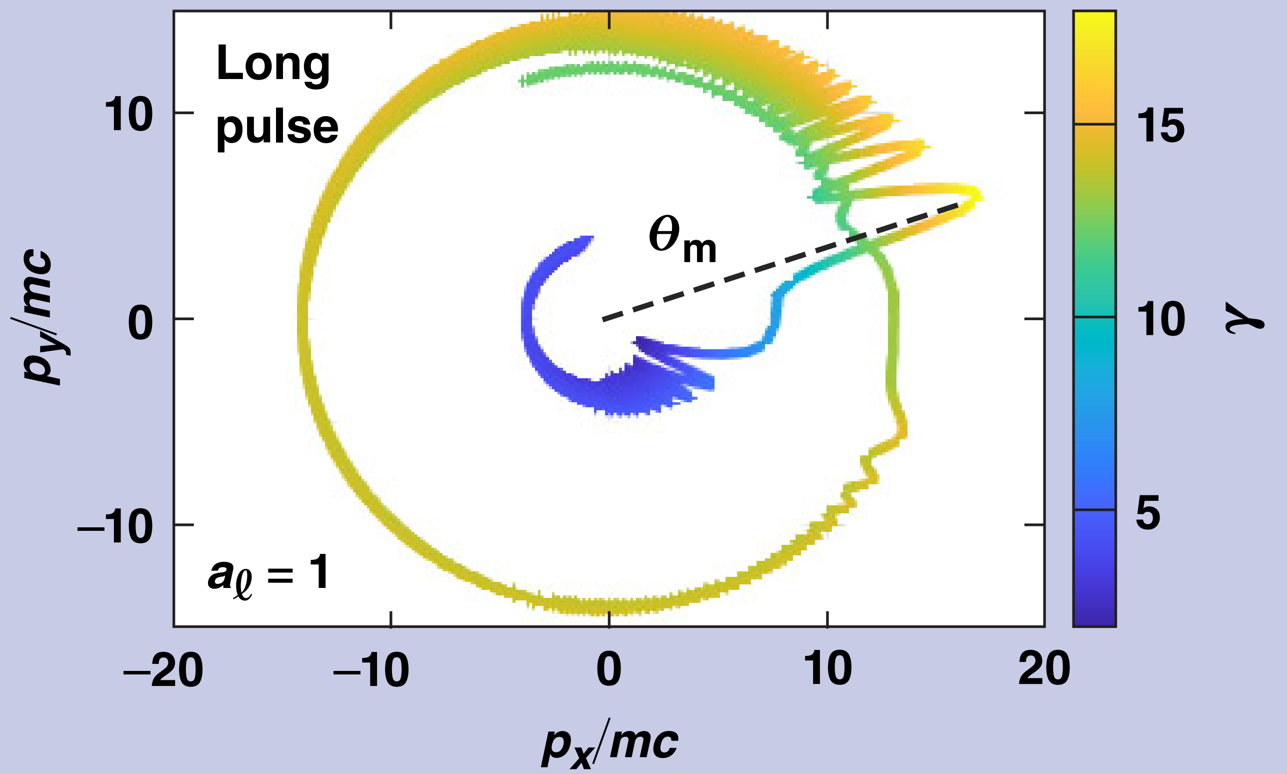
Single-particle picture of heating



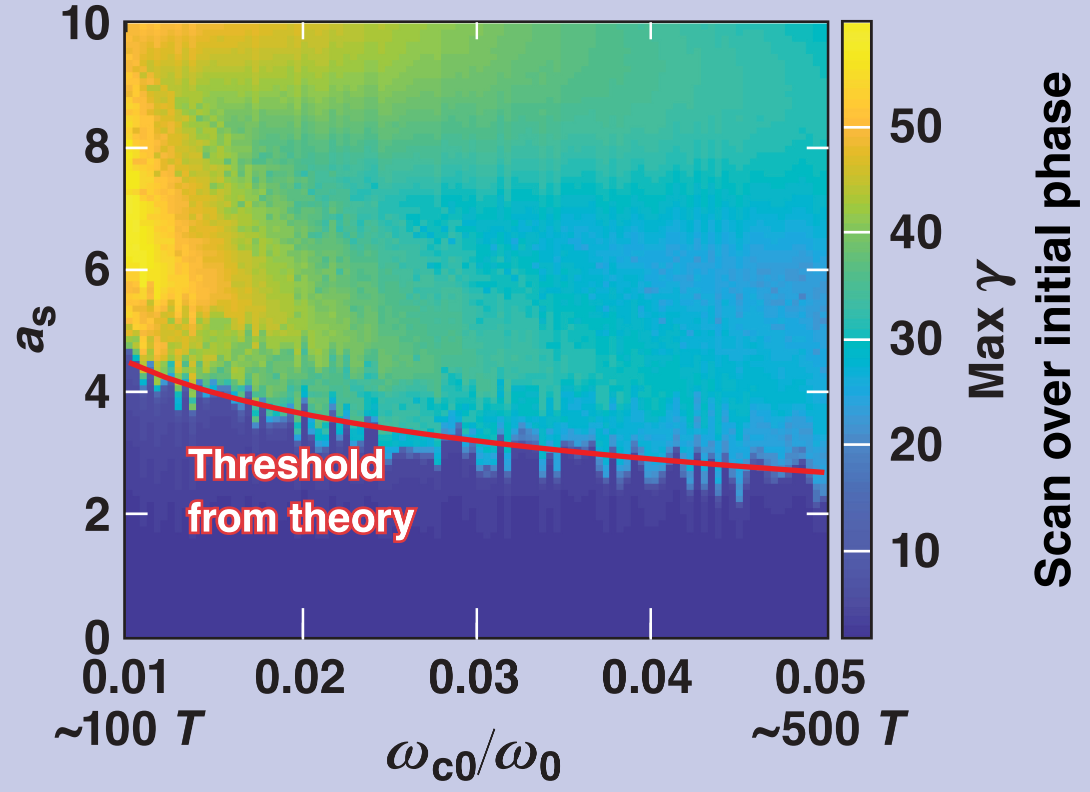
Step 1: multi-cycle acceleration by short pulse



Step 2: energy kicks by single cycle in long pulse



The short pulse is needed to catalyze long-pulse heating



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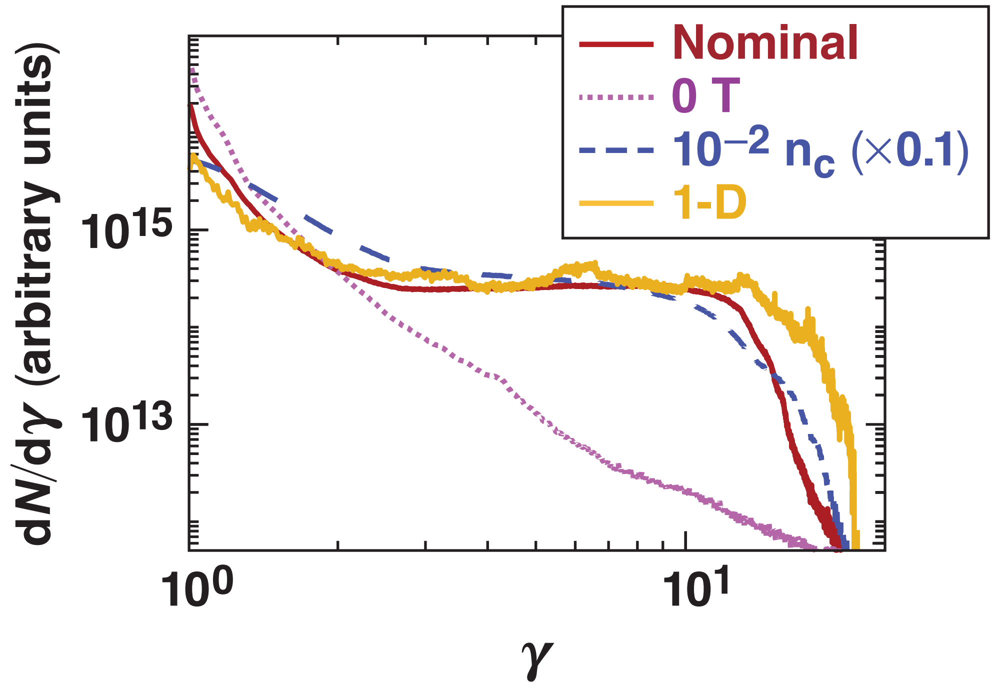
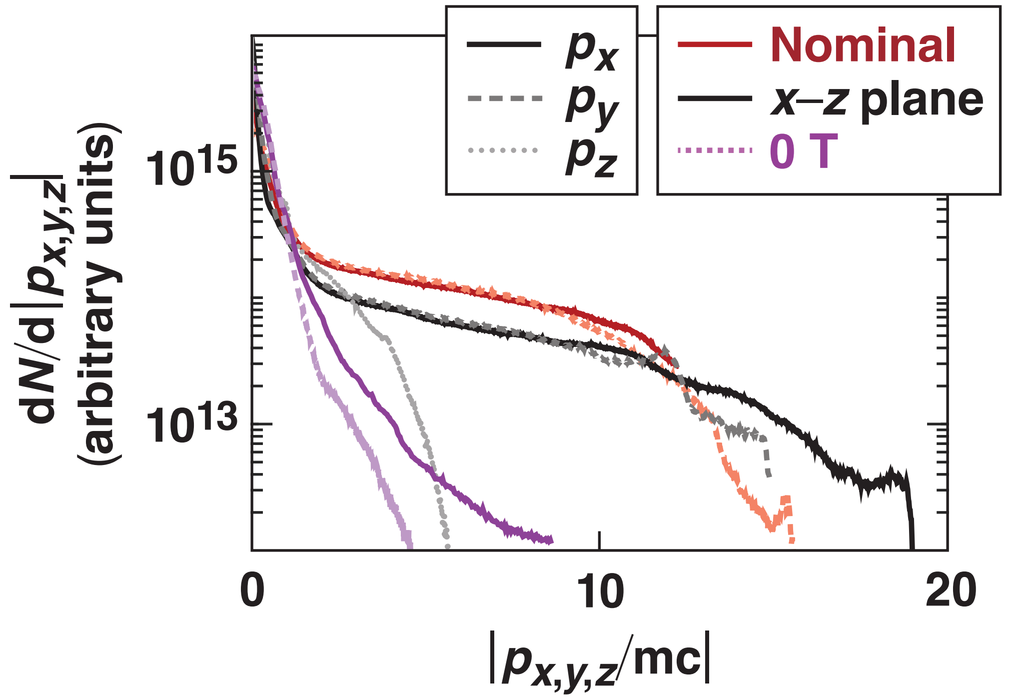
Bulk-relativistic plasma is generated with 2-D isotropic momentum

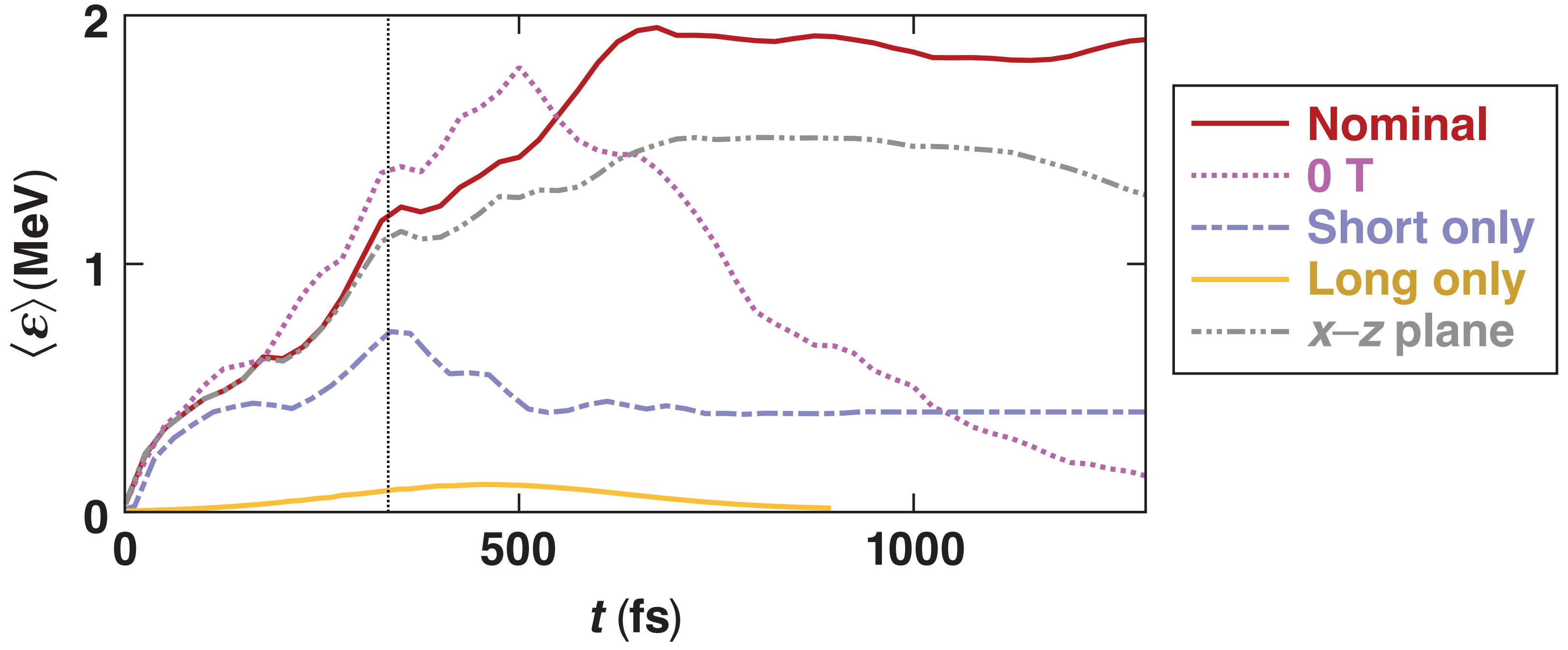
Spectra for $|r| < 25\ \mu$m





Hot plasma persists beyond laser pulse duration

Average energy of all electrons in $|r| < 25\ \mu$m



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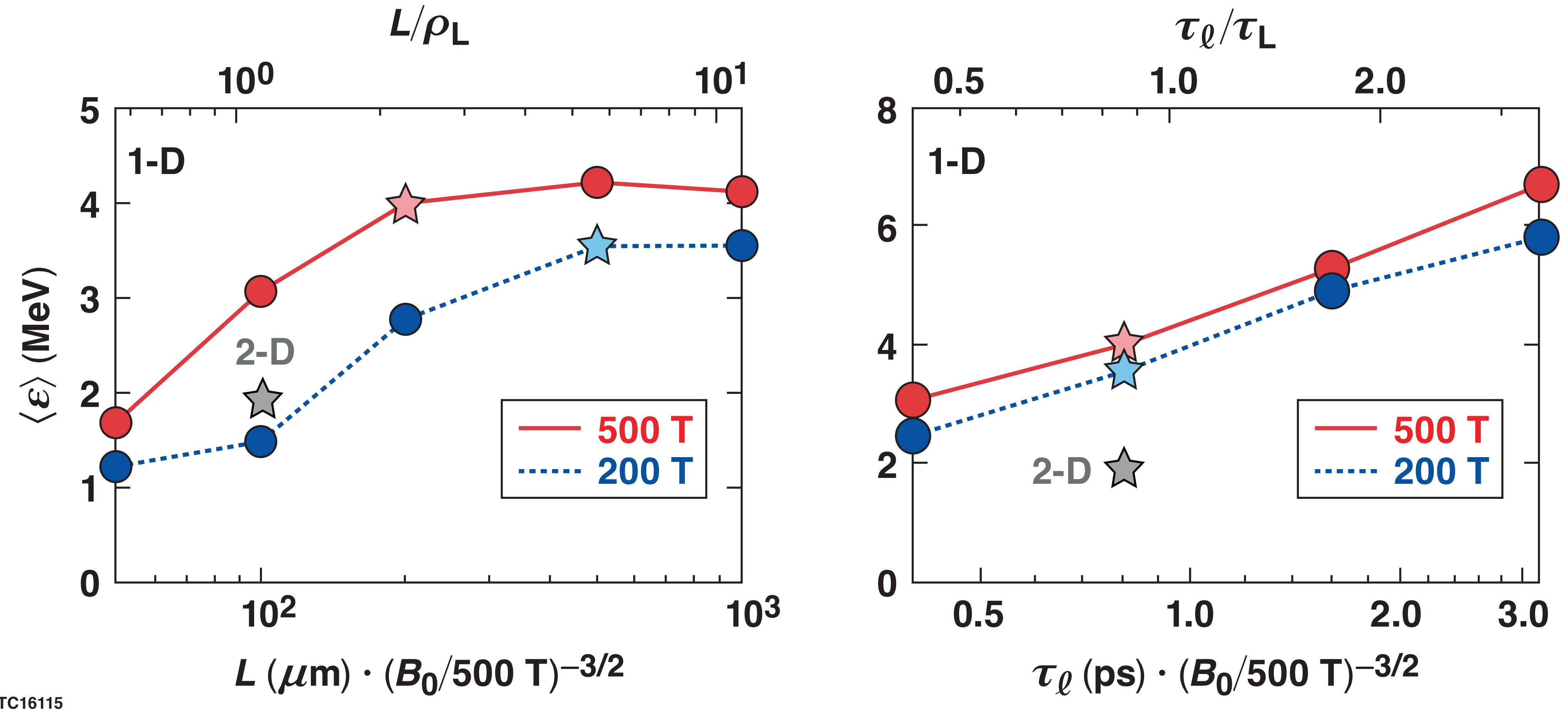

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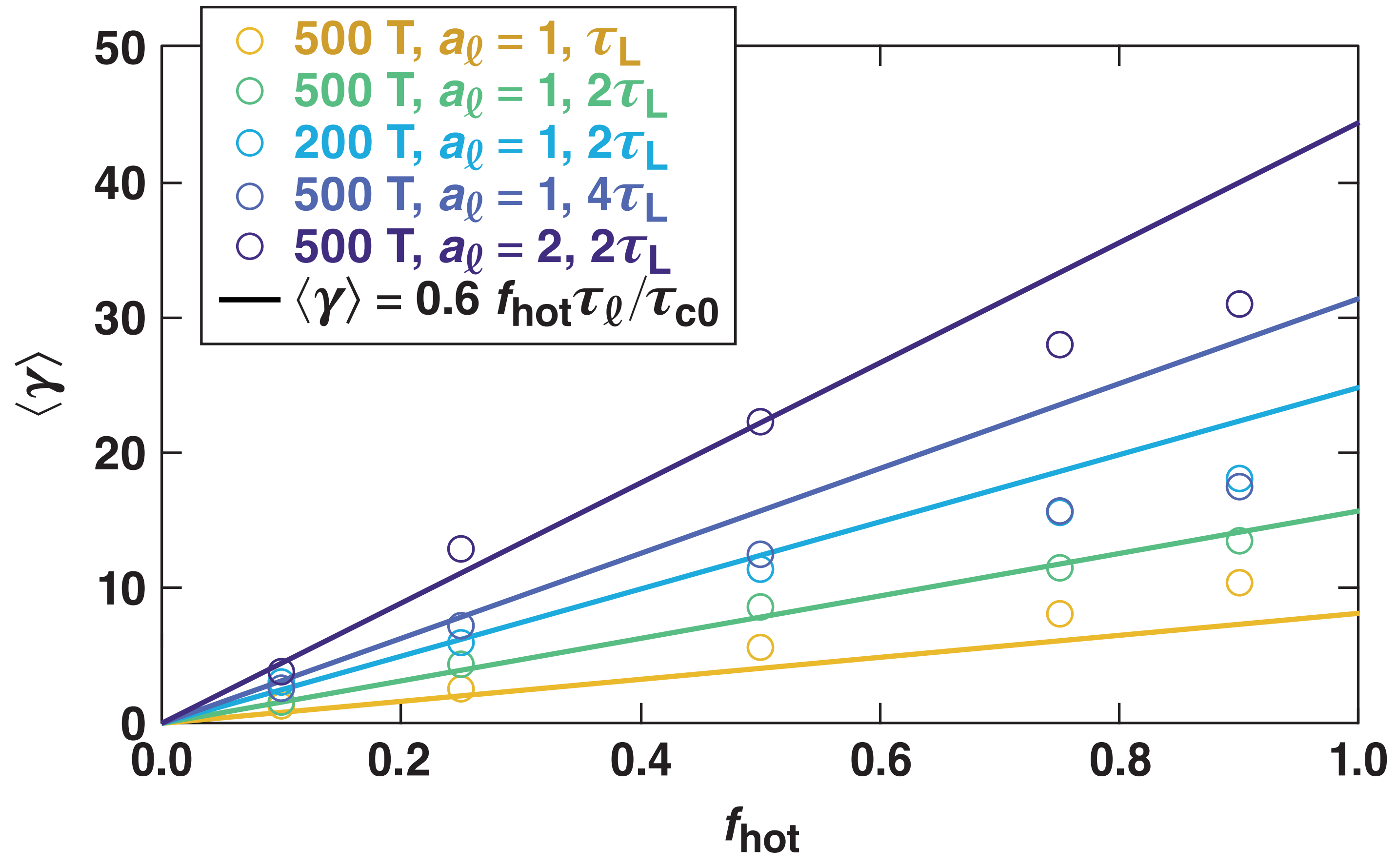

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