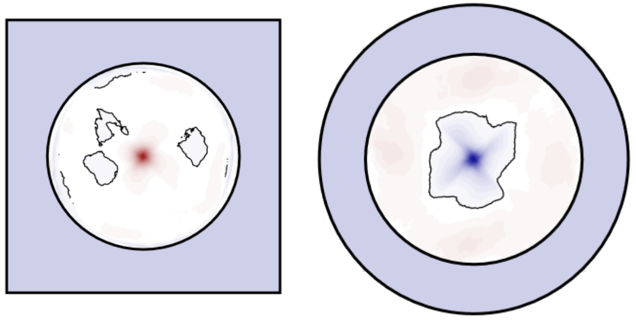
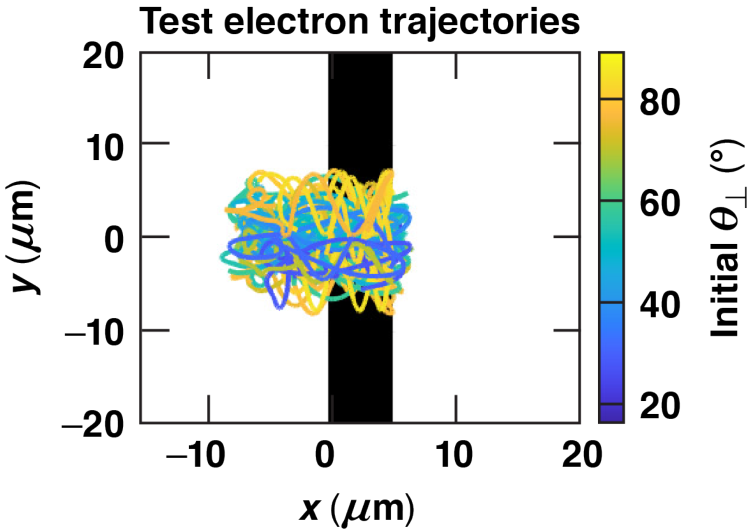
Effects of Kilotesla-Level Magnetic Fields on Relativistic Laser–Plasma Interaction

UR LLE

Magnetic-field generation

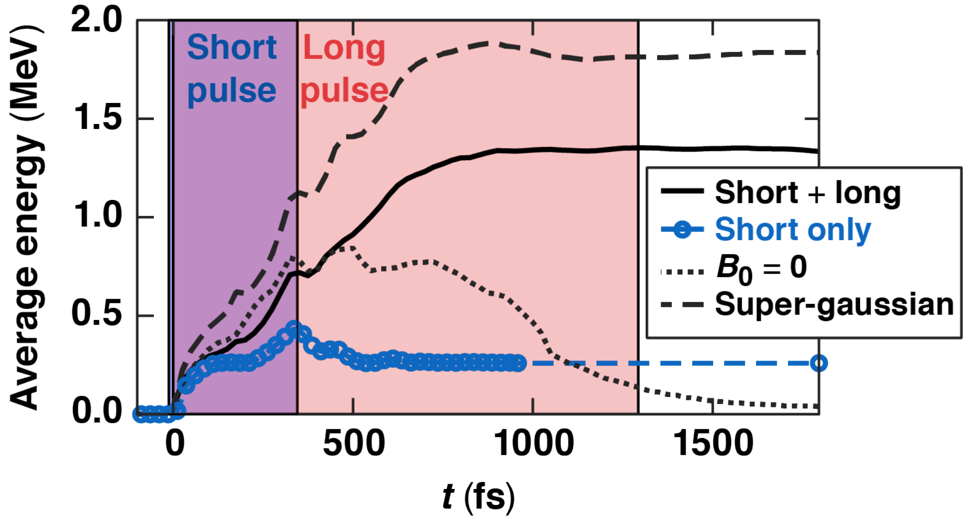


Plasma expansion and sheaths



TC15821a

Direct laser acceleration and plasma heating



TC15827a

K. Weichman
Pronouns: they/them
University of Rochester
Laboratory for Laser Energetics

63rd Annual Meeting of the APS Division of Plasma Physics
8 – 12 November 2021

Summary

Kilotesla-level applied magnetic fields introduce new possibilities for relativistic laser–plasma interaction

- Currently available magnetic fields appear “weak” by bulk metrics, yet are sufficiently strong to influence laser-plasma dynamics
- Laser plasmas with embedded magnetic fields do not always behave diamagnetically
- Applied magnetic fields can dramatically change plasma expansion
- Kilotesla or subkilotesla fields can enable new forms of direct laser acceleration-based heating
- Applied magnetic fields open the door to many additional phenomena

Near-term experimentally relevant magnetic fields enable new, useful phenomena in relativistic laser–plasma interactions.

Collaborators

A. V. Arefiev, H. Mao, and F. N. Beg

J. P. Palastro

A. P. L. Robinson

M. Murakami and S. Fujioka

J. J. Santos

T. Toncian

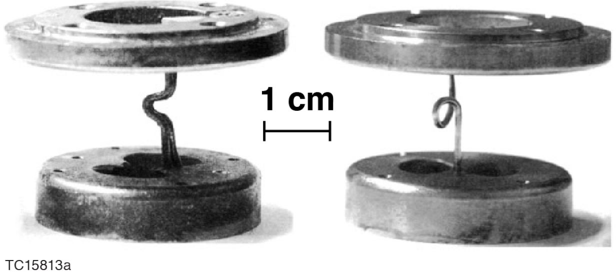
T. Ditmire and H. Quevedo

Y. Shi

V. V. Ivanov

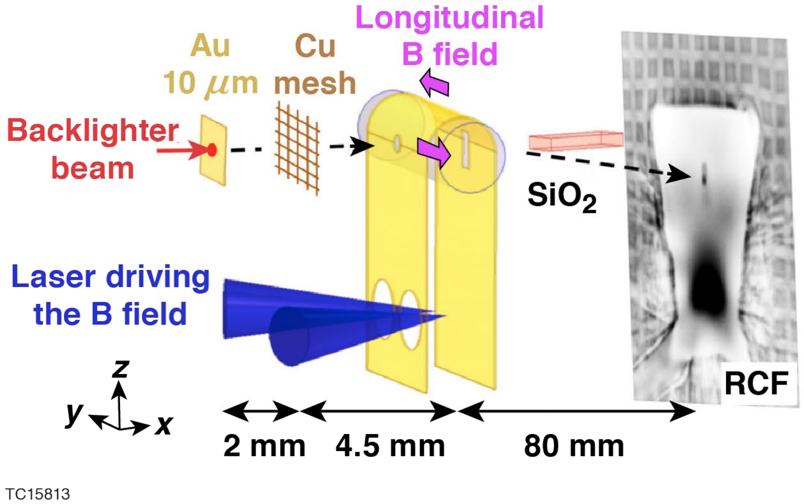
How strong are experimentally available magnetic fields?

- "Obvious" effects require strong magnetic fields
  - $B_0 > B_{\text{laser}}$
  - cyclotron resonance ($\omega_{\text{ce}} \gtrsim \omega_{\text{laser}}$)
  - direct magnetization ($\beta_e = \frac{8\pi n_e T_e}{B_0^2} < 1$)

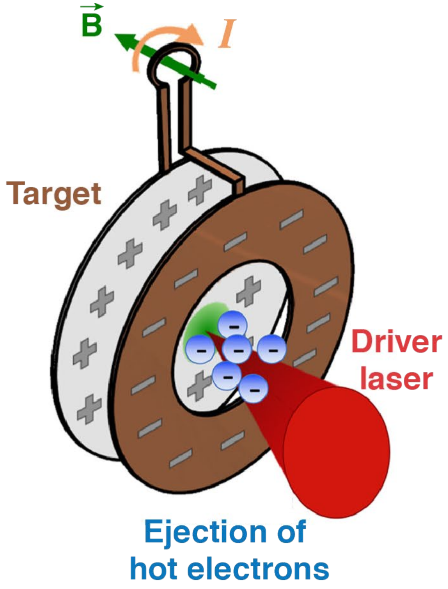


V. V. Ivanov *et al.*, Rev. Sci. Instrum. 89, 033504 (2018).

G. Fiksel *et al.*, Rev. Sci. Instrum. 86, 016105 (2015).



C. Goyon *et al.*, Phys. Rev. E 95, 033208 (2017).



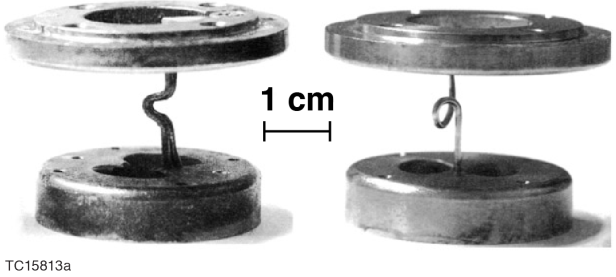
J. J. Santos *et al.*, Phys. Plasmas 25, 056705 (2018).

RCF: radiochromic film

How strong are experimentally available magnetic fields?

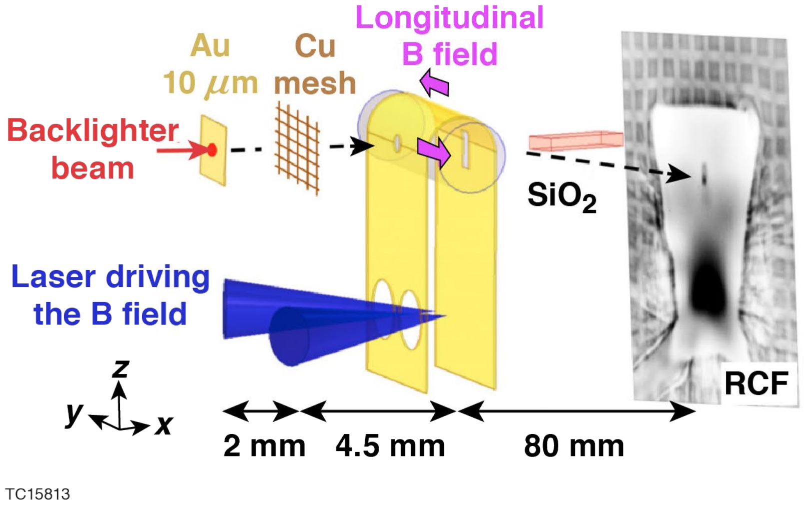
- "Obvious" effects require strong magnetic fields
  - $B_0 > B_{\mathrm{laser}}$
  - cyclotron resonance ($\omega_{\mathrm{ce}} \gtrsim \omega_{\mathrm{laser}}$)
  - direct magnetization ($\beta_e = \frac{8\pi n_e T_e}{B_0^2} < 1$)
- State-of-the art magnetic fields reach 100 T to 1 kT
- Compare to fs- to ps-duration pulses with $a_0 = \frac{|e|E_{\mathrm{laser}}}{m_e c\omega_{\mathrm{laser}}} \sim 1-3$:
  - $B_0/B_{\mathrm{laser}} \lesssim 1/10$
  - $\omega_{\mathrm{ce}}/\omega_{\mathrm{laser}} \lesssim 1/10$
  - $\beta_e \gtrsim 20$

A kilotesla magnetic field is "weak" by bulk metrics, yet can still have a strong impact.

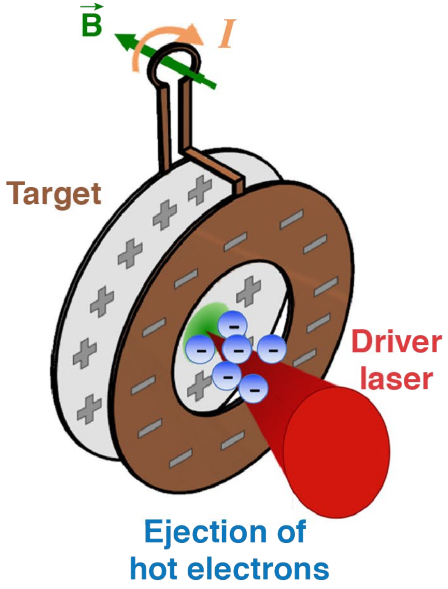


V. V. Ivanov *et al.*, Rev. Sci. Instrum. 89, 033504 (2018).

G. Fiksel *et al.*, Rev. Sci. Instrum. 86, 016105 (2015).



C. Goyon *et al.*, Phys. Rev. E 95, 033208 (2017).

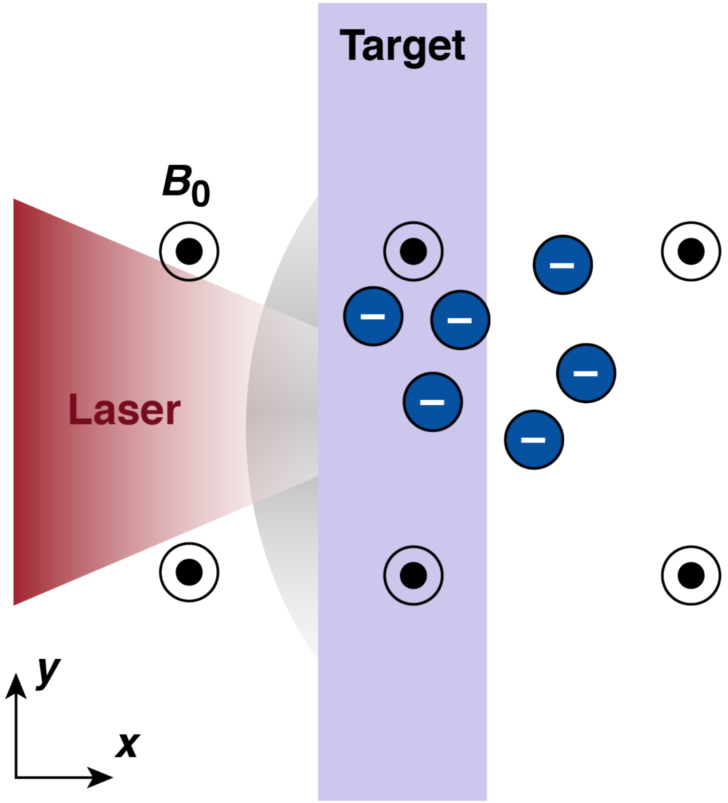


J. J. Santos *et al.*, Phys. Plasmas 25, 056705 (2018).

RCF: radiochromic film

A relativistic laser produced plasma is not always diamagnetic and can generate magnetic fields

B_{z0} = 100 T to 1 kT



TC15814a

Opaque target

2-μm thick CH $< \rho_L$
0.1-μm preplasma scale length

Laser

1×10^{19} W/cm^2
100 fs FWHM
λ = 0.8 μm
y polarized

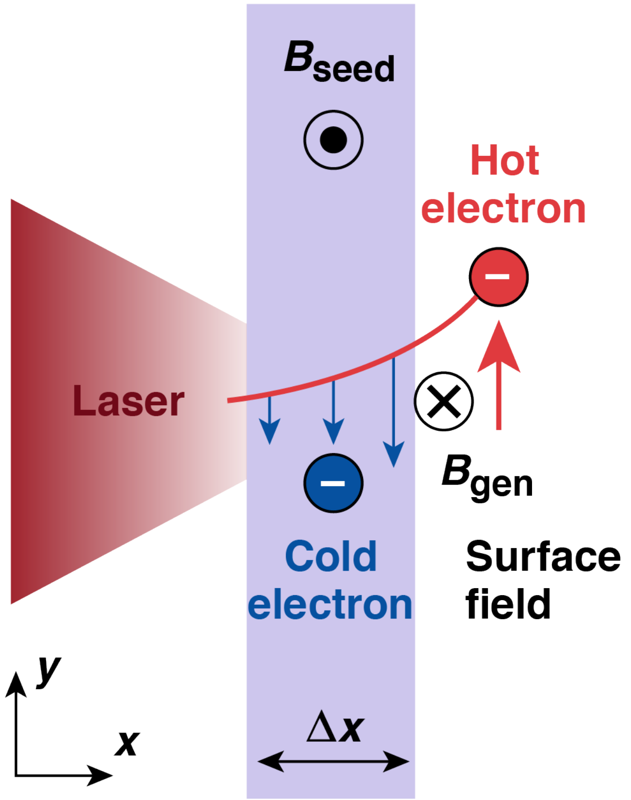
Simulations

1-D and 2-D
EPOCH PIC code

- (Hypothetical) diamagnetic picture
  - laser generates hot plasma
  - current in hot plasma reduces the applied magnetic field

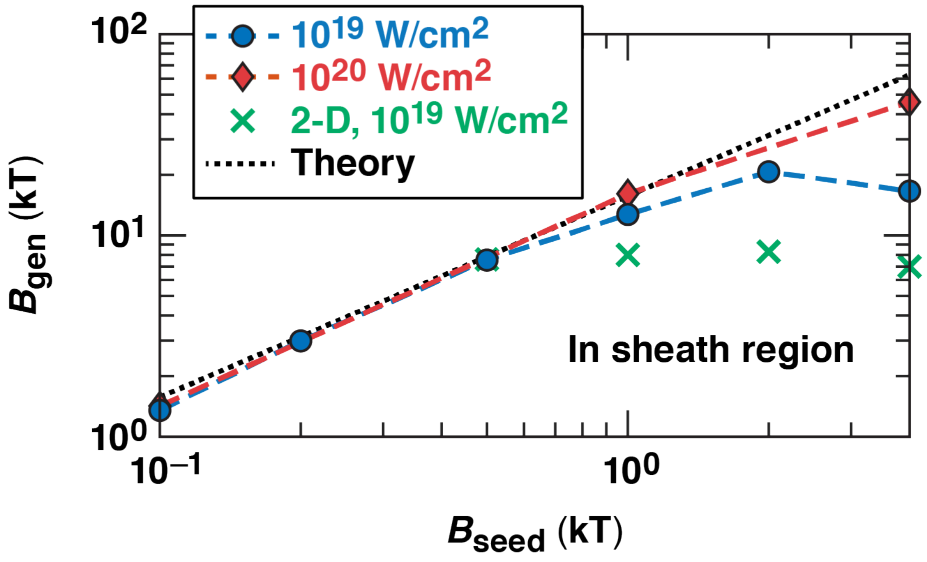
K. Weichman *et al*., New J. Phys. 22, 113009 (2020).
PIC: particle in cell

Surface field generation is an overshoot of the diamagnetic effect



TC15814

- Cyclotron rotation of hot electrons originating at the laser–plasma interface leads to a net transverse current
- Hot electron current is screened by cold population within the target, allowing it to overshoot the usual diamagnetic limit
- The magnetic-field estimate based on cyclotron rotation agrees well with observed fields (for $\Delta x < \rho_L$)



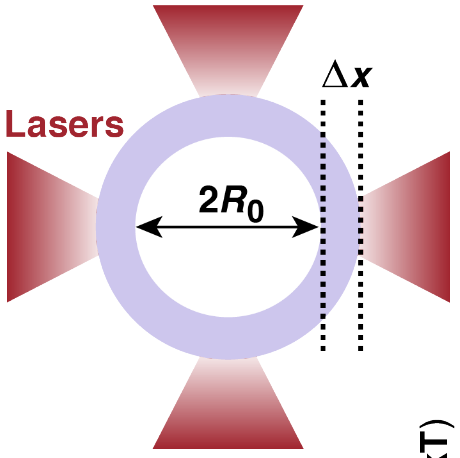
TC15815

Surface magnetic field generation is a kinetic effect.

K. Weichman *et al.*, New J. Phys. 22, 113009 (2020).

Surface magnetic-field generation can have surprising consequences

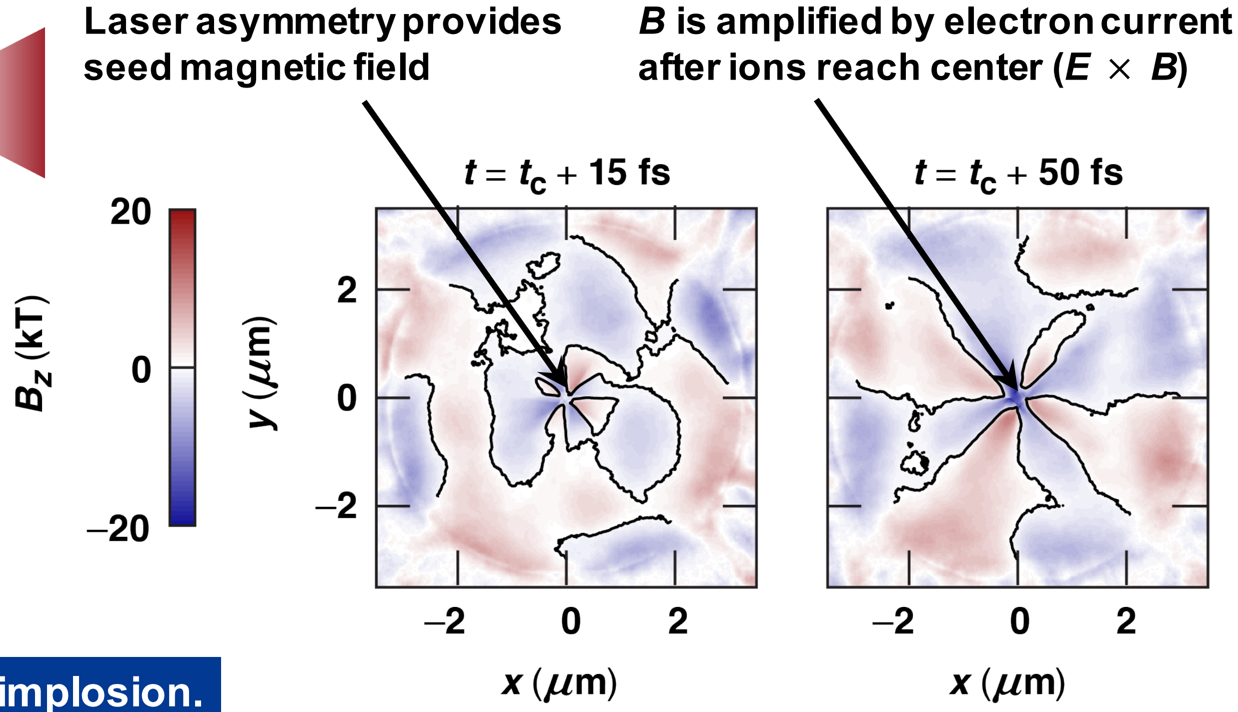
- Microtube implosions generate and amplify magnetic fields
- Microtube target
  - 3-μm thick CH shell
  - 3-μm radius central void
  - four lasers
- Lasers
  - 1×10^{21} W/cm^2
  - 15 μm FWHM
  - 25 fs FWHM
  - $\lambda = 0.8$ μm
  - y polarized



TC15816

2-D PIC simulation

Initially unmagnetized (B_{z0} = 0) case



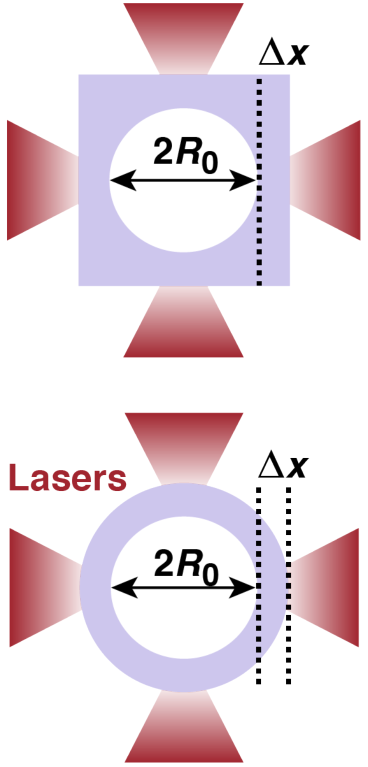
Any magnetic field present can be amplified by the implosion.

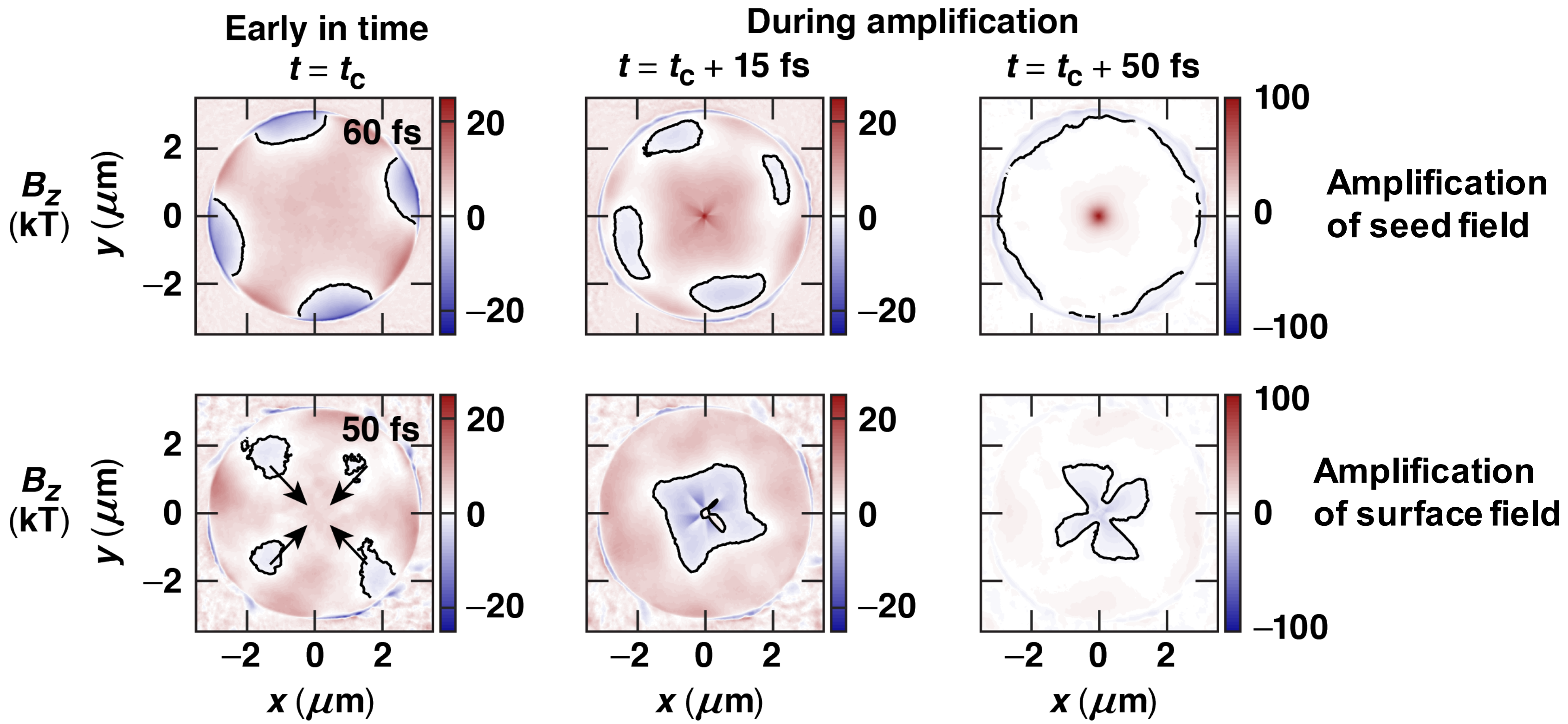
M. Murakami *et al.*, Sci. Rep. 10, 16653 (2020).
K. Weichman *et al.*, Appl. Phys. Lett. 117, 244101 (2020).

The sign of the amplified field can be reversed due to surface magnetic-field generation

Seed magnetic fields enable strong magnetic-field generation

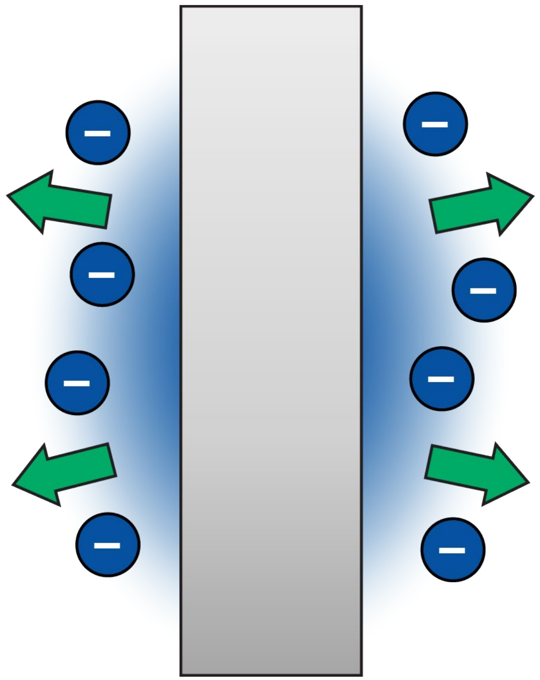
B_{z0} = 3 kT



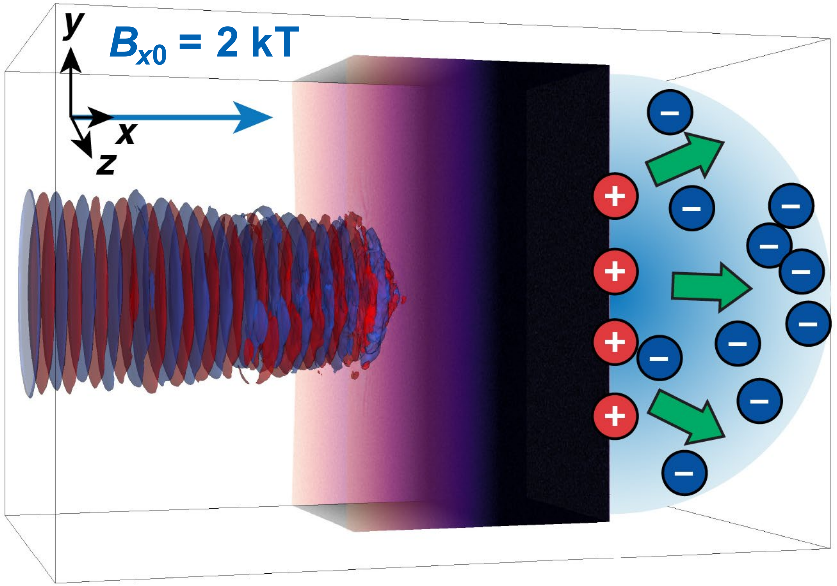


K. Weichman *et al.*, Appl. Phys. Lett. 117, 244101 (2020).

Plasma expansion and sheaths



Target-normal applied magnetic fields can enhance sheath-based ion acceleration



TC15819

Opaque target

5-μm thick CH
1.5-μm-preplasma scale length

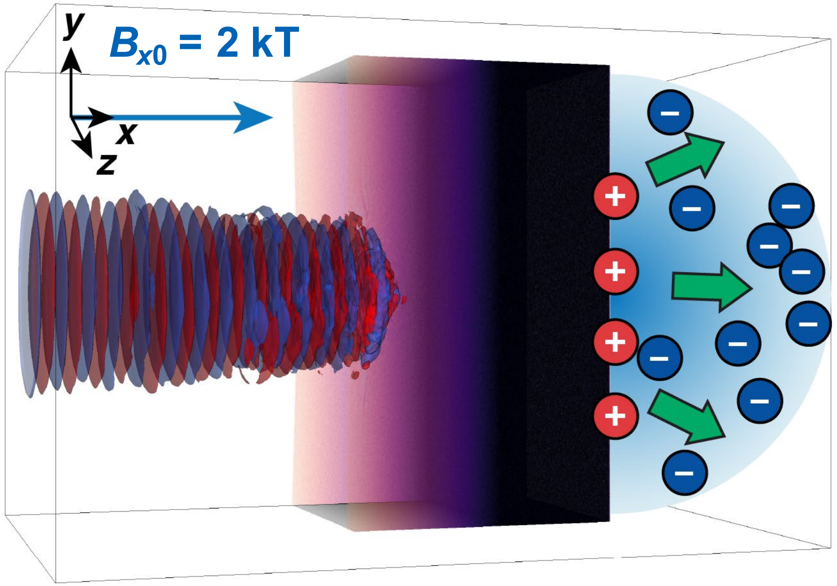
3-D simulation

Laser

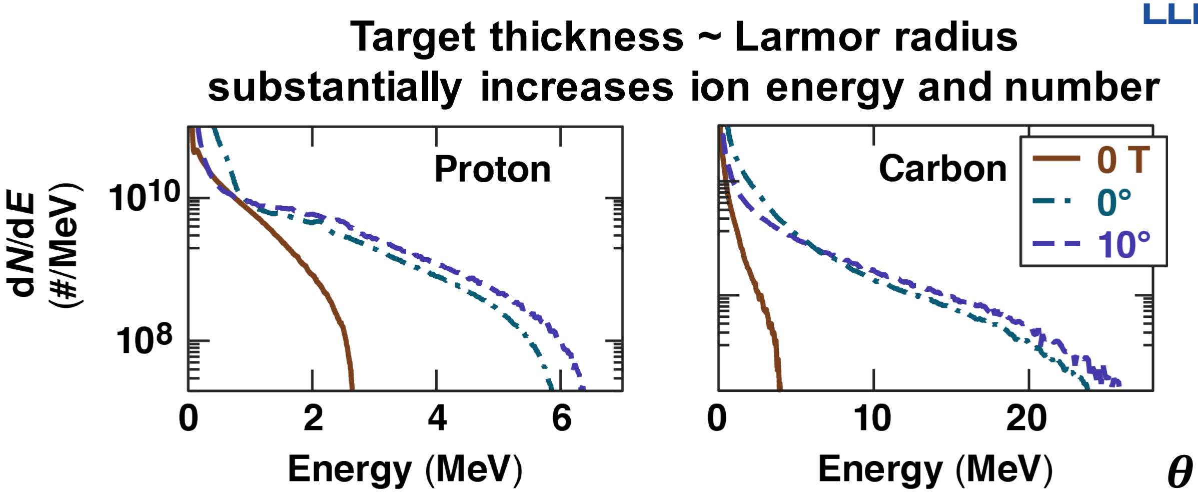
2×10^{19} W/cm^2
3 μm FWHM
150 fs FWHM
$\lambda = 1$ μm
y polarized

K. Weichman *et al.*, Sci. Rep. 10, 18966 (2020).

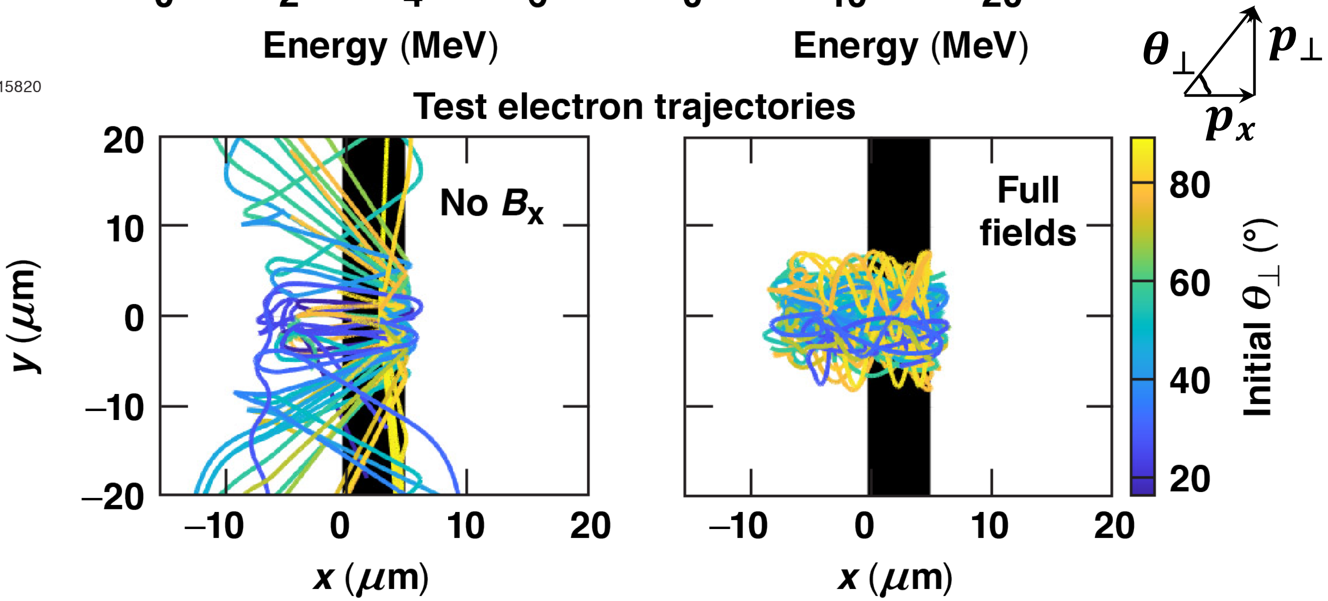
Target-normal applied magnetic fields can enhance sheath-based ion acceleration



TC15819



TC15820



TC15821

Opaque target

5-μm thick CH
1.5-μm-preplasma scale length

3-D simulation

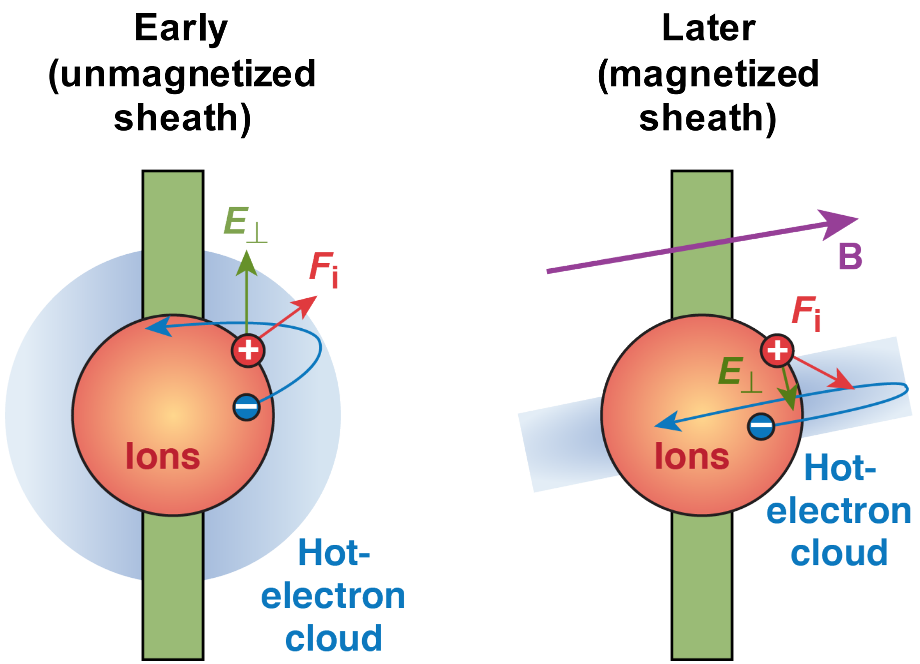
Laser

2×10^{19} W/cm^2
3 μm FWHM
150 fs FWHM
λ = 1 μm
y polarized

K. Weichman *et al.*, Sci. Rep. 10, 18966 (2020).

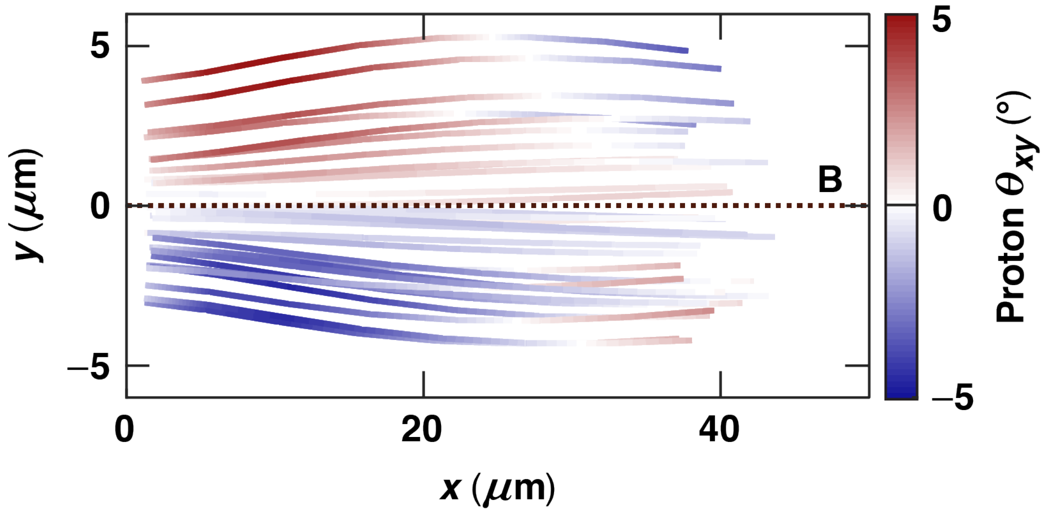
(Eventual) magnetization of sheath induces ion focusing

Magnetization: $\frac{E_{\text{sheath}}}{B_0} \sim \sqrt{\frac{4\pi n_e T_e}{B_0^2}} \sim \sqrt{\beta_e} \lesssim 1$



TC15822

- Initially $\beta_e > 1$, but n_e (and β_e) drop during plasma expansion
- Change in $E_\perp$ leads to ion focusing

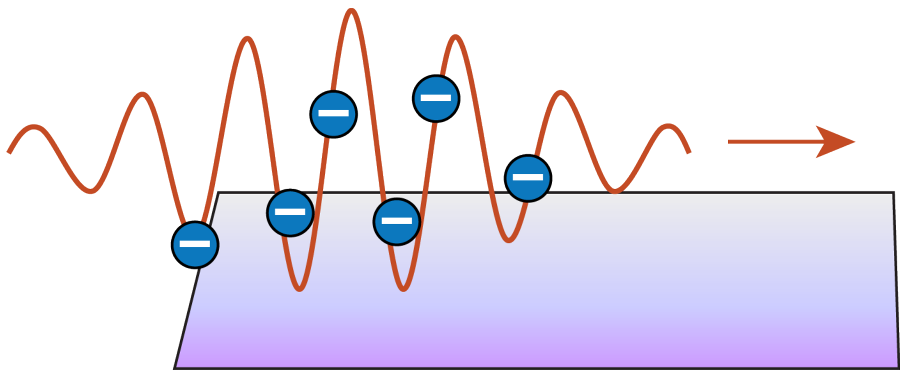


TC15823

A target-normal magnetic field produces a focusing ion source with enhanced energy and numbers.

K. Weichman *et al.*, Sci. Rep. 10, 18966 (2020).

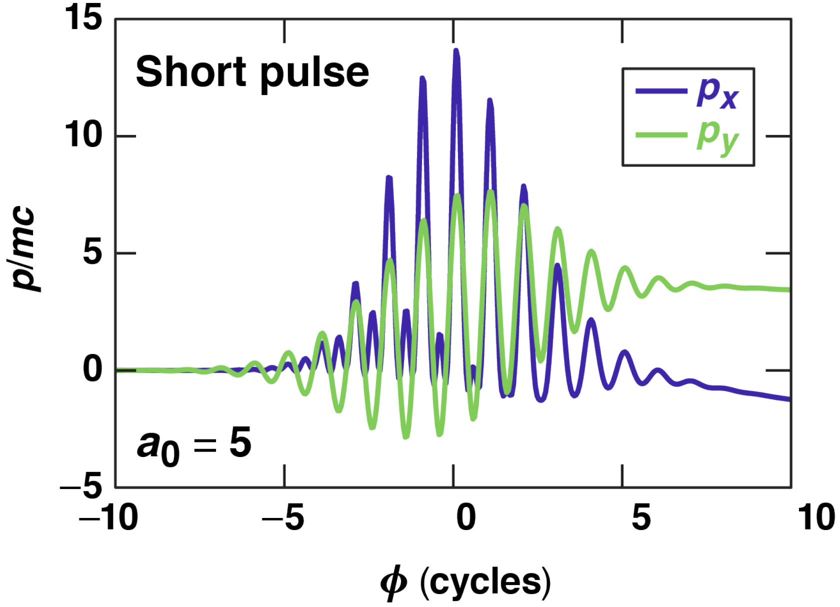
Direct laser acceleration and plasma heating



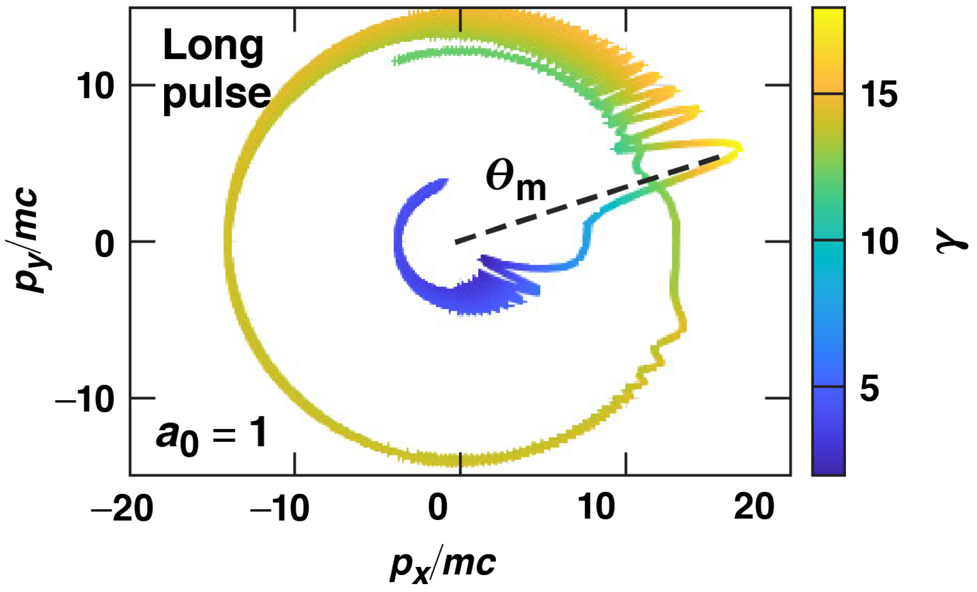
Applied magnetic fields enable new regimes in direct laser acceleration

A transverse magnetic field (B_{z0} with y-polarized laser) enables electron energy retention

- Partial cyclotron rotation
  - initially cold plasma
  - pulse duration < cyclotron period
  - $\gamma_{\text{final}} \lesssim a_0$



- Magnetically assisted kicks
  - initially hot plasma
  - pulse duration ≫ cyclotron period
  - $\gamma_{\text{final}} \sim a_0^{3/2} (\omega_{\text{laser}}/\omega_{\text{ce}})^{1/2}$

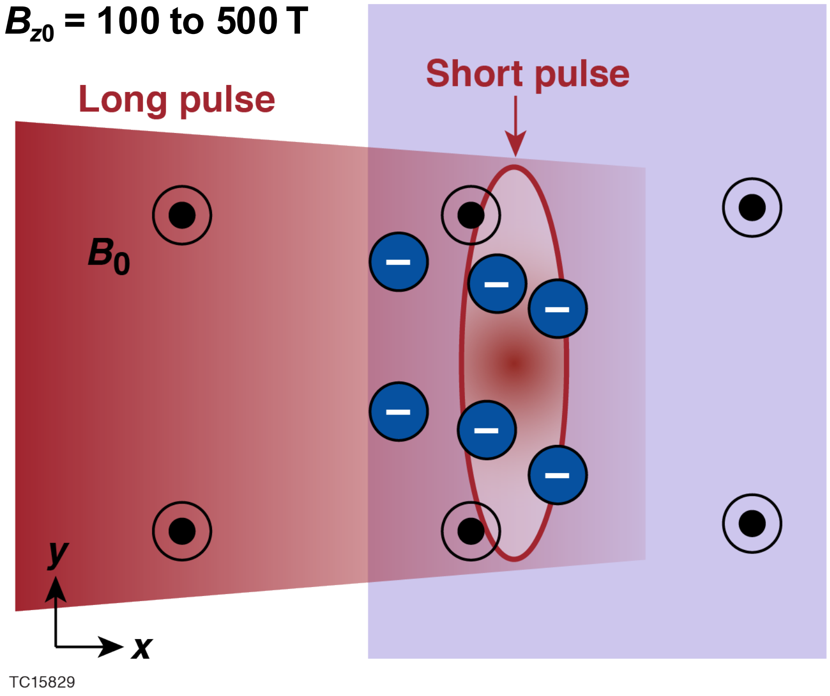


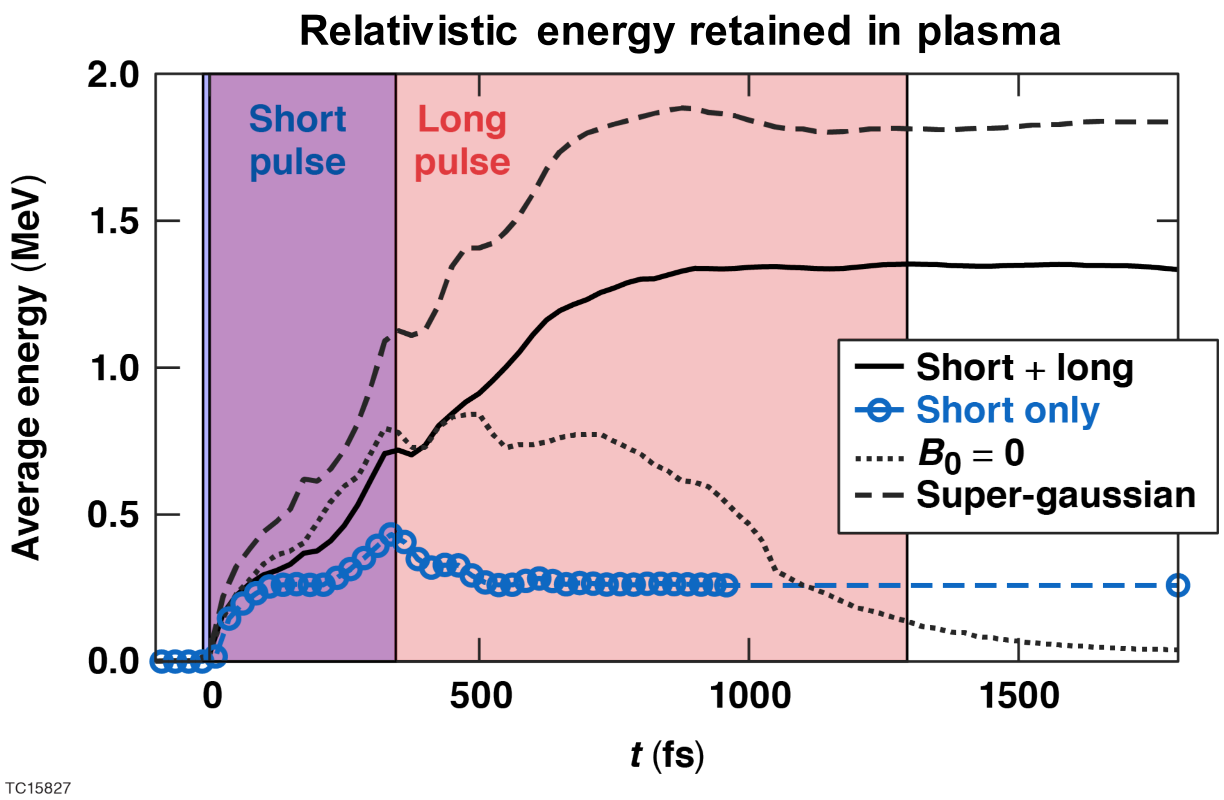
TC15824

These acceleration strategies can be combined.

A. P. L. Robinson and A. V. Arefiev, Phys. Plasmas 27, 023110 (2020).
A. Arefiev, Z. Gong, and A. P. L. Robinson, Phys. Rev. E 101, 043201 (2020).

Magnetized direct laser acceleration can create a relativistic, underdense thermal plasma





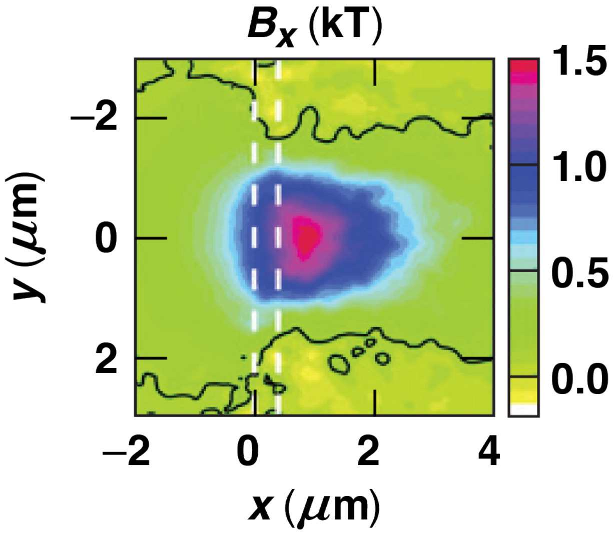
	Femtosecond laser	Picosecond laser	Both lasers
	$a_0 = 5$ 20 fs FWHM	$a_0 = 1$ 0.8 ps FWHM	100 μm FWHM $\lambda = 1\ \mu$m
Plasma		10^{-3} to 10^{-2} n_c 100-μm–thick-H	2-D simulation

Magnetic fields enable relativistic plasma generation in an otherwise difficult-to-access regime.

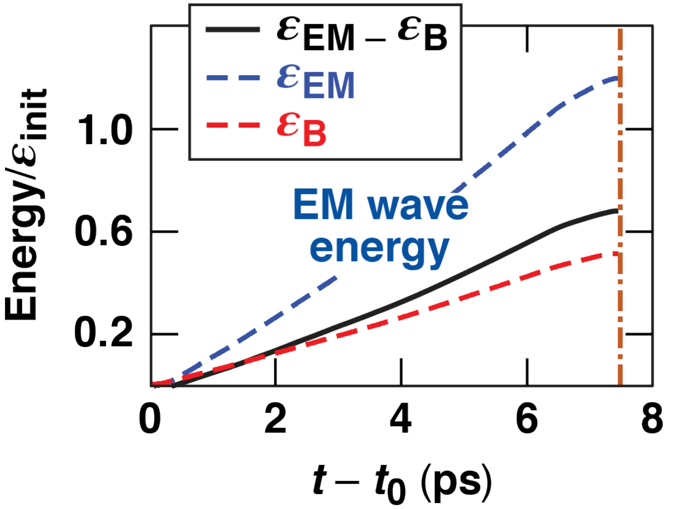
Magnetized relativistic laser-plasma physics offers many additional phenomena

A few examples

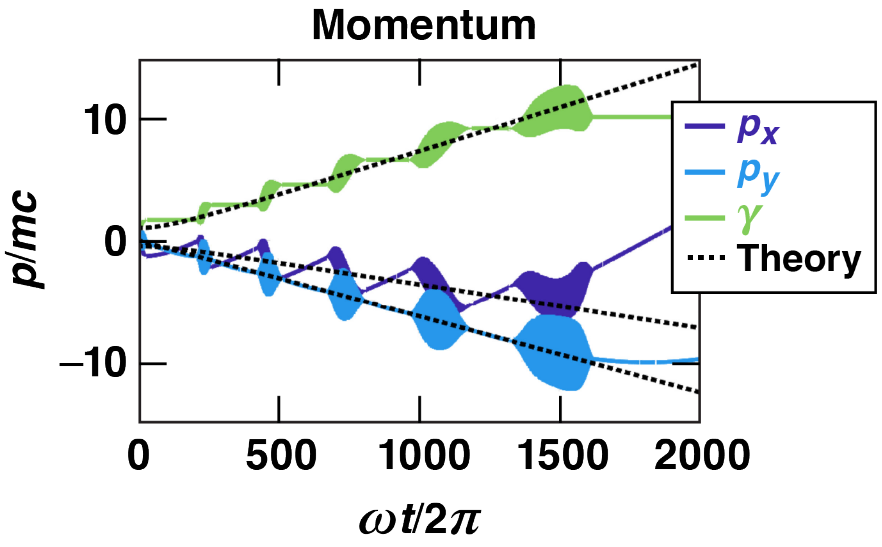
Magnetic-field amplification in a solid by return current*



Electromagnetic wave generation during plasma expansion into neutral gas**



Multiple cycles of ponderomotive energy gain (e.g., by a flying focus pulse)



TC15828

* Y. Shi *et al.*, New J. Phys. 22, 073067 (2020).
**H. Mao *et al.*, Phys. Rev. E 103, 023209 (2021).

Kilotesla-level applied magnetic fields introduce new possibilities for relativistic laser–plasma interaction

- Currently available magnetic fields appear “weak” by bulk metrics, yet are sufficiently strong to influence laser-plasma dynamics
- Laser plasmas with embedded magnetic fields do not always behave diamagnetically
- Applied magnetic fields can dramatically change plasma expansion
- Kilotesla or subkilotesla fields can enable new forms of direct laser acceleration-based heating
- Applied magnetic fields open the door to many additional phenomena

Near-term experimentally relevant magnetic fields enable new, useful phenomena in relativistic laser–plasma interactions.

Backup slides

Scale comparison for 1 kT

Typical parameters for modestly relativistic laser-plasma

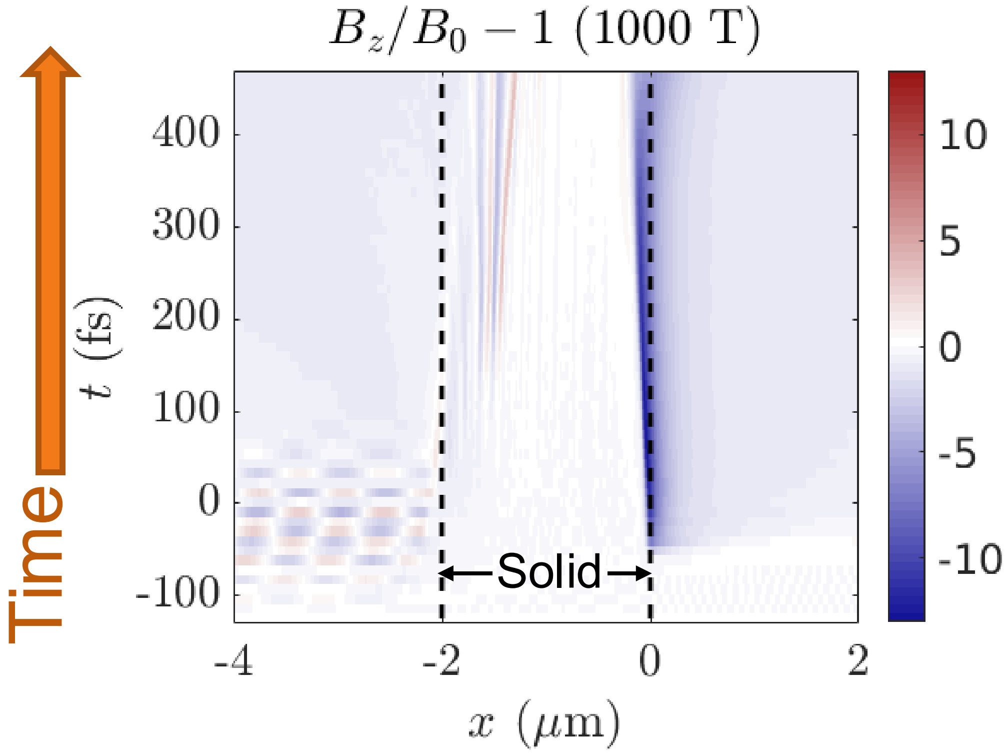
Laser parameters	Value
Laser amplitude	$a_0 = \|e\|E_0/m_e c\omega \sim 1-3$ $(\sim 10^{19}\ \mathrm{W/cm^2})$
Pulse duration	100 fs – 10 ps

Plasma parameters	Value
Hot electron temperature	$T_e \sim \mathrm{MeV}$
Plasma density (hot part)	$n_e \sim 10^{-4} - 1\ n_{cr}$ $\sim 10^{17} - 10^{21}\ cm^{-3}$

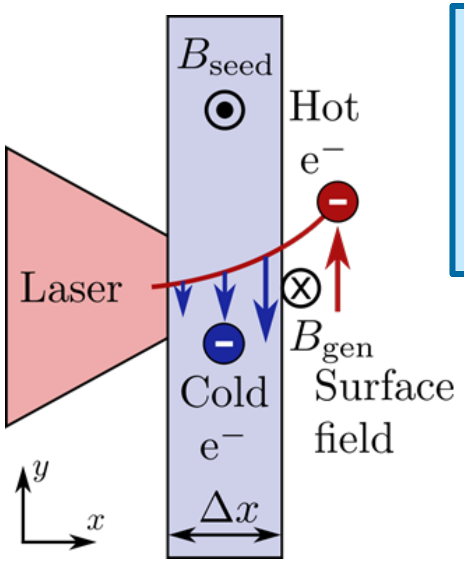
Laser-plasma scales	Magnetic field scales	Comparison
Laser frequency	Cyclotron frequency	$\omega_{laser}/\omega_{ce} \gtrsim 10$
Laser field B_{laser}	Applied field B_0	$B_{laser}/B_0 \gtrsim 10$
Thermal pressure	Magnetic field pressure	$\beta_e = 8\pi n_e T_e/B_0^2 \sim 20-500$
Scale of electron motion l	Larmor radius ρ_L	$\rho_L/\mathrm{l} \sim 1-10$

Surface magnetic field generation

$\mathbf{B_{z0}}$ = 1 kT generates > 10 kT

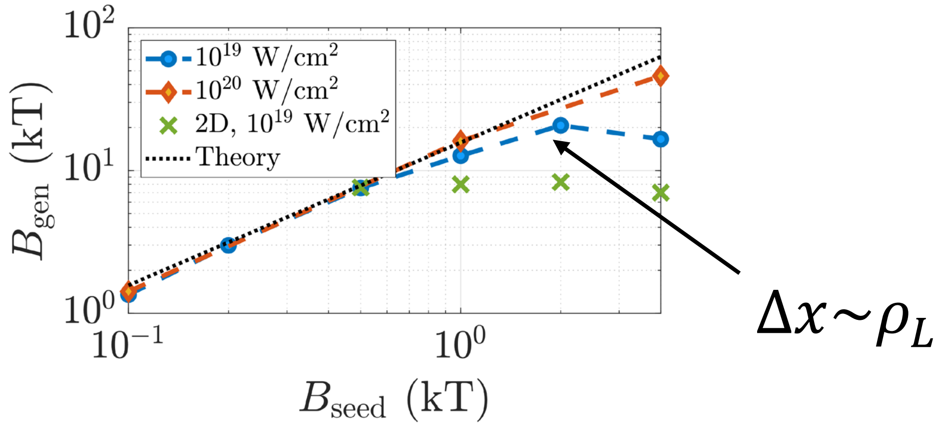


Strong magnetic field generation is due to cyclotron rotation of hot electrons in target



Estimate based on momentum rotation in target ($\Delta x < \rho_L$)

$$\frac{B_{gen}}{B_{seed}} \sim -2\pi \frac{\Delta x}{\lambda_{laser}}$$

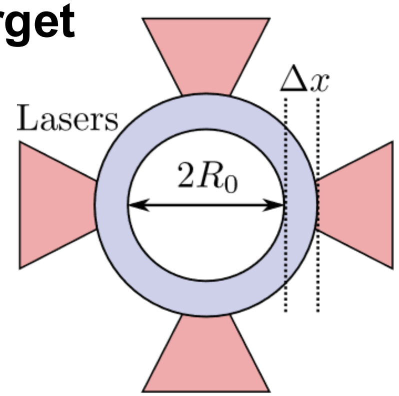


Surface magnetic field generation can have surprising consequences

Microtube implosions generate and amplify magnetic fields

Microtube target

3 μm thick CH shell
3 μm radius central void
4 lasers



Lasers

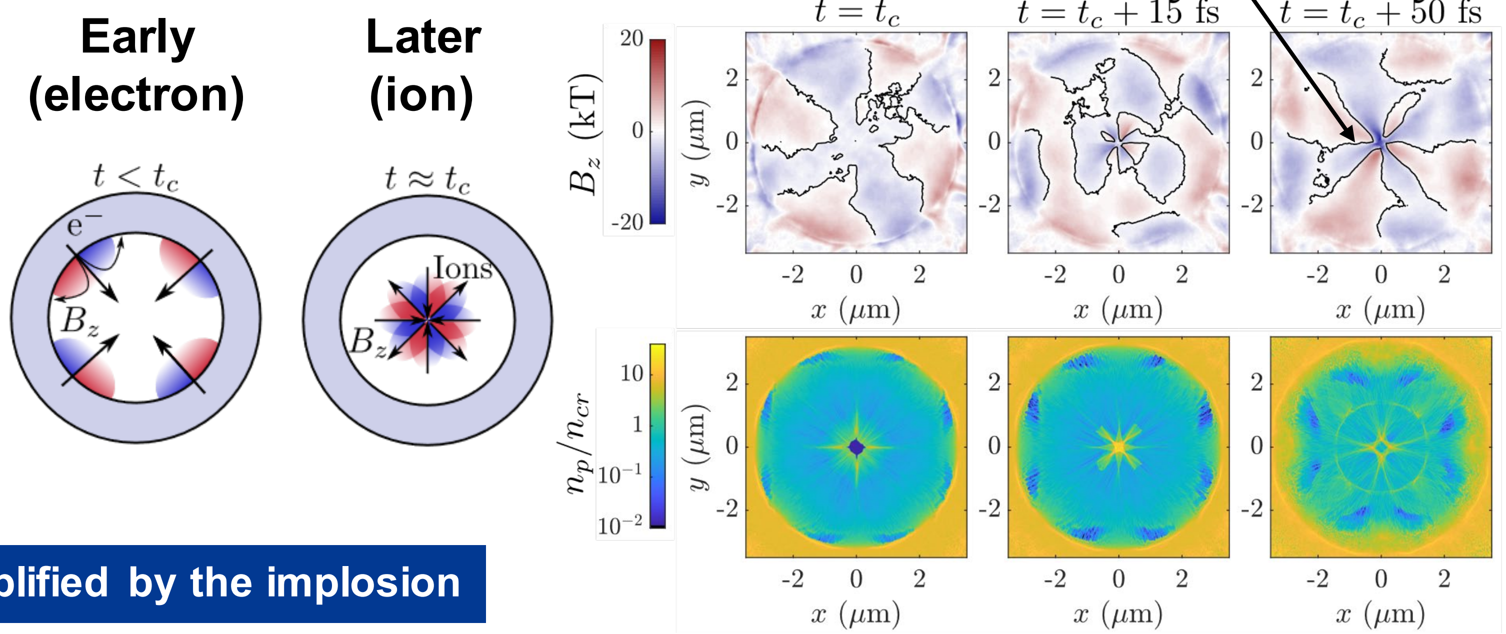
$1\text{x}10^{21}$ W/cm^2
15 μm FWHM
25 fs FWHM
$\lambda = 0.8\ \mu m$
y-polarized

2D PIC simulation

Initially unmagnetized $(B_{z0} = 0)$ case

Asymmetry provides seed magnetic field

B is amplified by electron current after ions reach center $(E \times B)$



Any magnetic field present can be amplified by the implosion

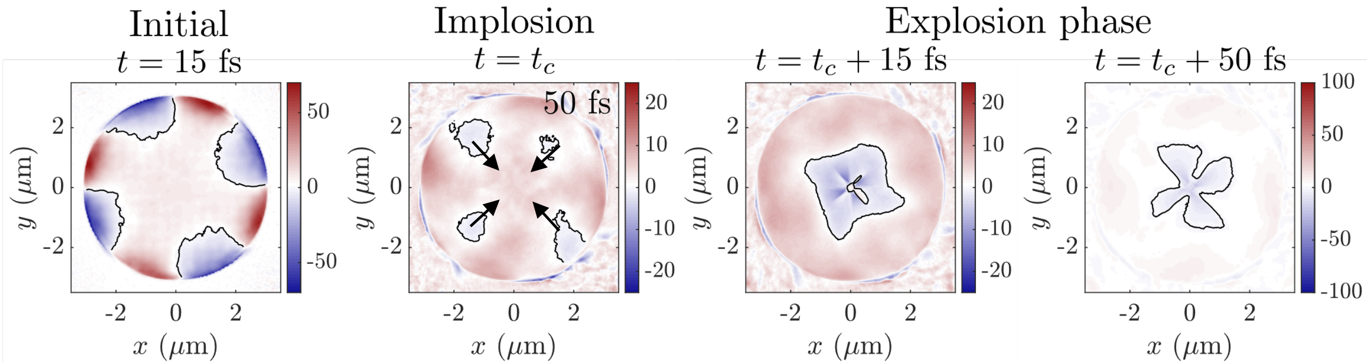
M. Murakami, *et al*., Sci Rep **10**, 18966 (2020)

K. Weichman, *et al*., Appl Phys Lett **117**, 244101 (2020)

Polarity of amplified field is sensitive to parameters

Amplification of surface field

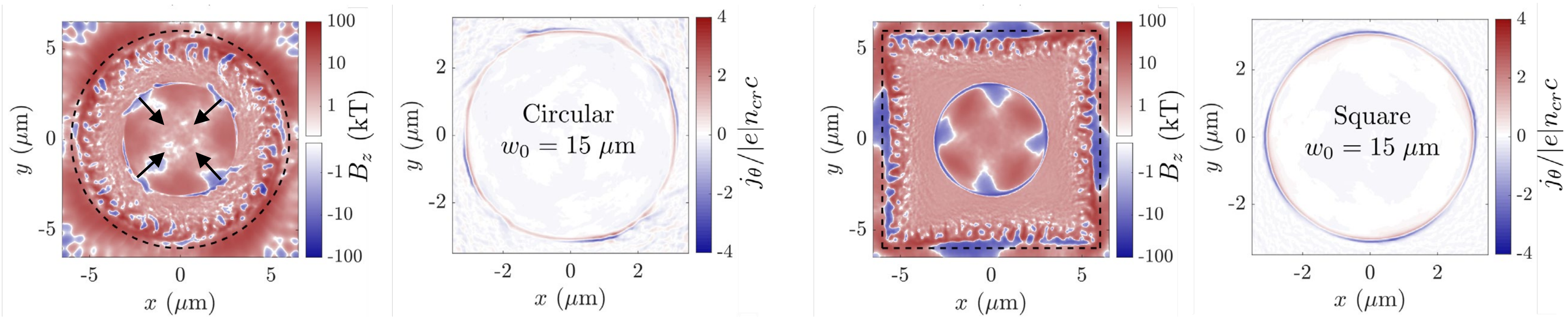
Circular case

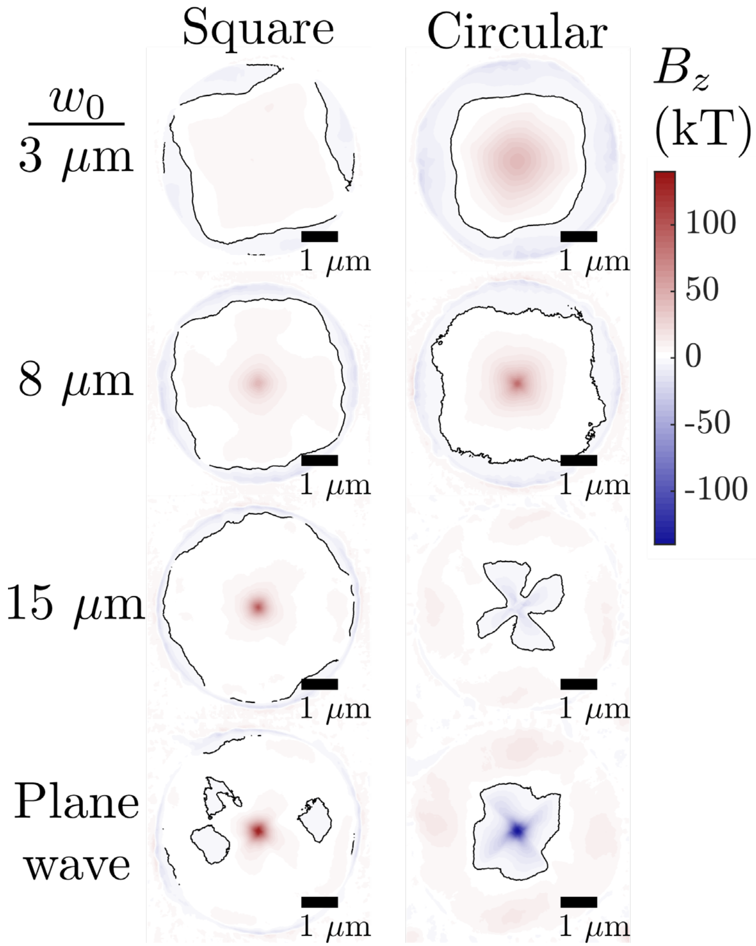


When surface magnetic field is unstable, it can be amplified in lieu of the seed

Unstable

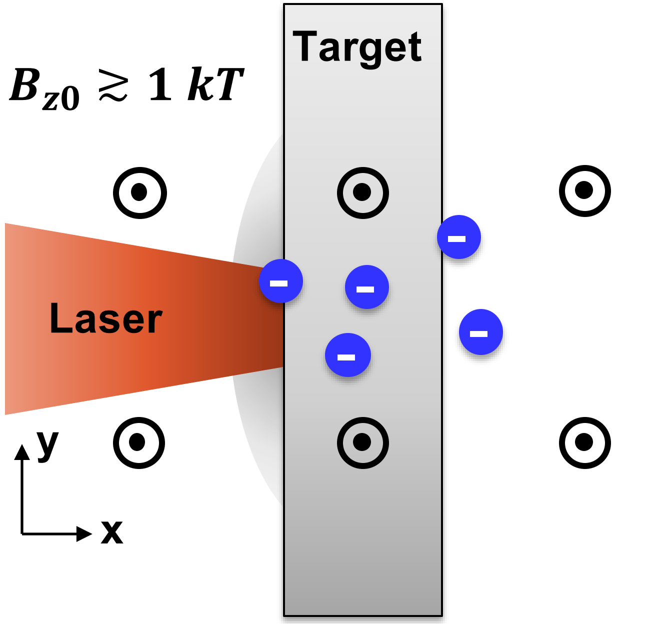
Stable





K. Weichman, *et al.*, Appl Phys Lett **117**, 244101

Transverse magnetic fields can also affect target expansion



Opaque target

2 μm thick CH
target $\gtrsim \rho_L$
0.1 μm preplasma
scale length

2D simulation

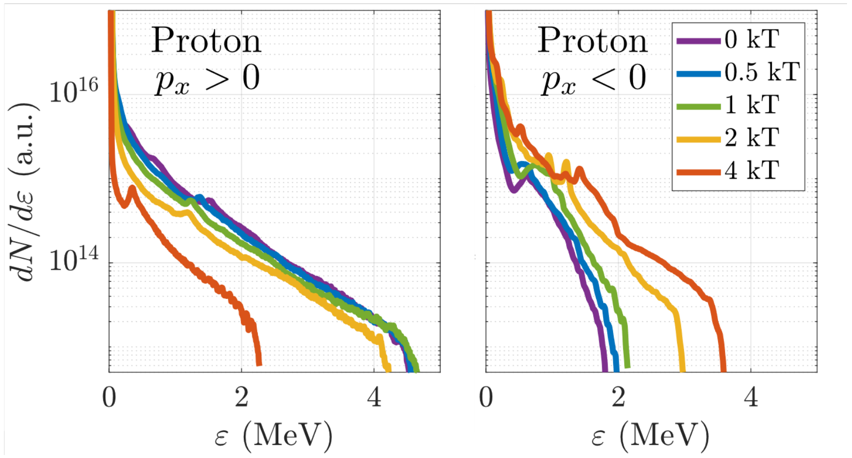
Laser

1x10^{19} W/cm^2
100 fs FWHM
$\lambda = 0.8\ \mu m$
y-polarized

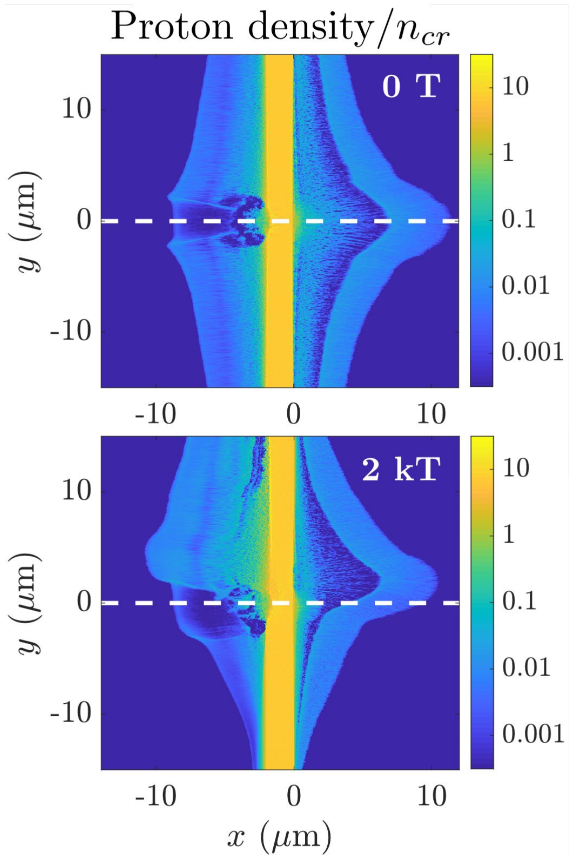
Unusual: acceleration from the front surface can exceed the rear surface

Rear surface (suppressed)

Front surface (enhanced)

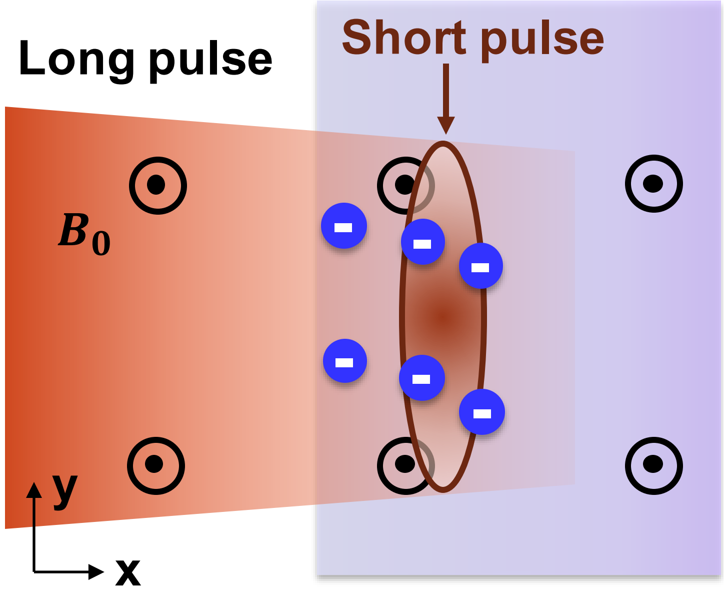


Deflection from laser axis

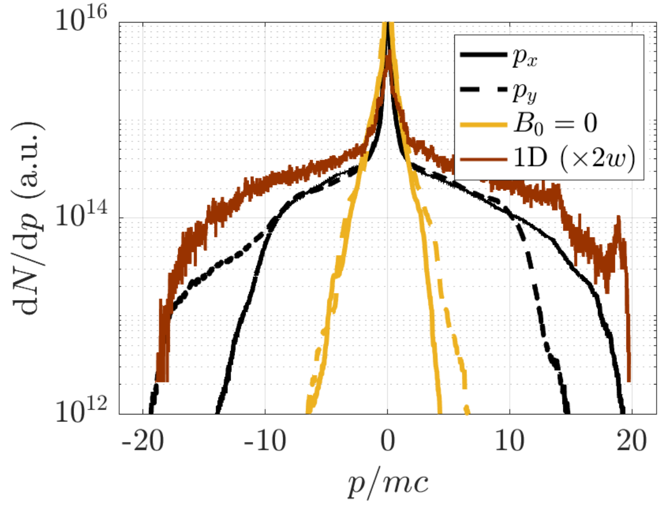


Magnetized direct laser acceleration can create relativistic, underdense thermal plasma

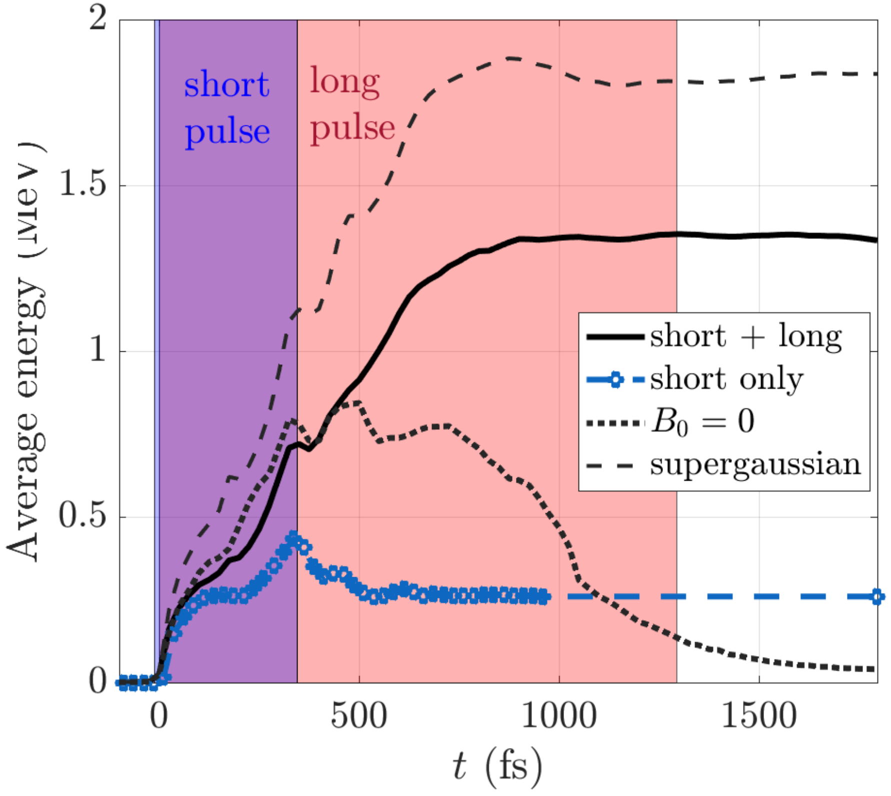
$B_{z0} = 100 - 500\ T$



(2D) isotropic spectrum



Relativistic energy

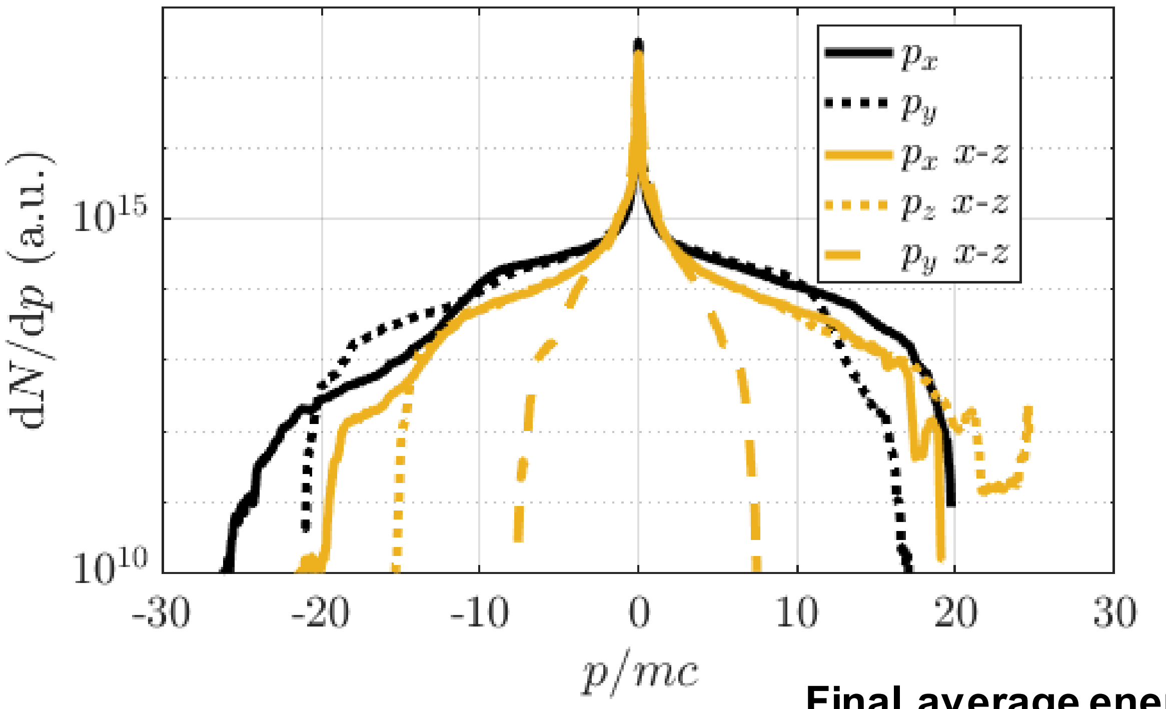


fs laser	ps laser	Both lasers
$a_0 = 5$	$a_0 = 1$	$100\ \mu m$ FWHM
20 fs FWHM	0.8 ps FWHM	$\lambda = 1\ \mu m$

Plasma $10^{-3} - 10^{-2} n_{cr}$ 100+ μm thick H — 2D simulation

Magnetic fields enable relativistic plasma generation in an otherwise difficult-to-access regime

Heating mechanism is robust to electron motion in the third direction



With $p_z \neq 0$

$$p_x = |p| \cos\theta$$

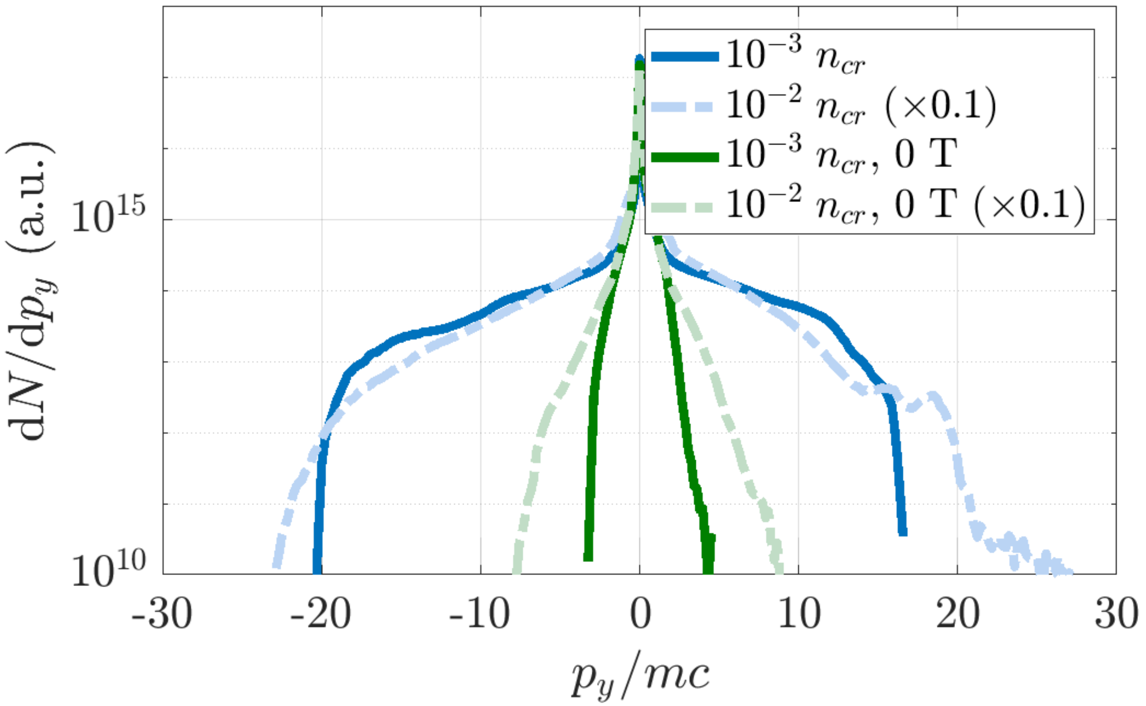
$$\frac{d\theta}{ds} = \sqrt{1 - \frac{p_z^2}{p_y^2 + p_z^2}} \cdot \frac{\frac{\omega_c}{\omega_0} + \left(\frac{1}{\beta}\cos\theta - 1\right)\frac{da}{ds}}{\gamma(1 - \beta\cos\theta)}$$

$$\frac{d\gamma}{ds} = \sqrt{1 - \frac{p_z^2}{p_y^2 + p_z^2}} \cdot \frac{\beta \sin\theta \frac{da}{ds}}{1 - \beta\cos\theta}$$

Final average energy: 0.9 MeV

Motion in third direction preserves θ during acceleration, but reduces energy gain

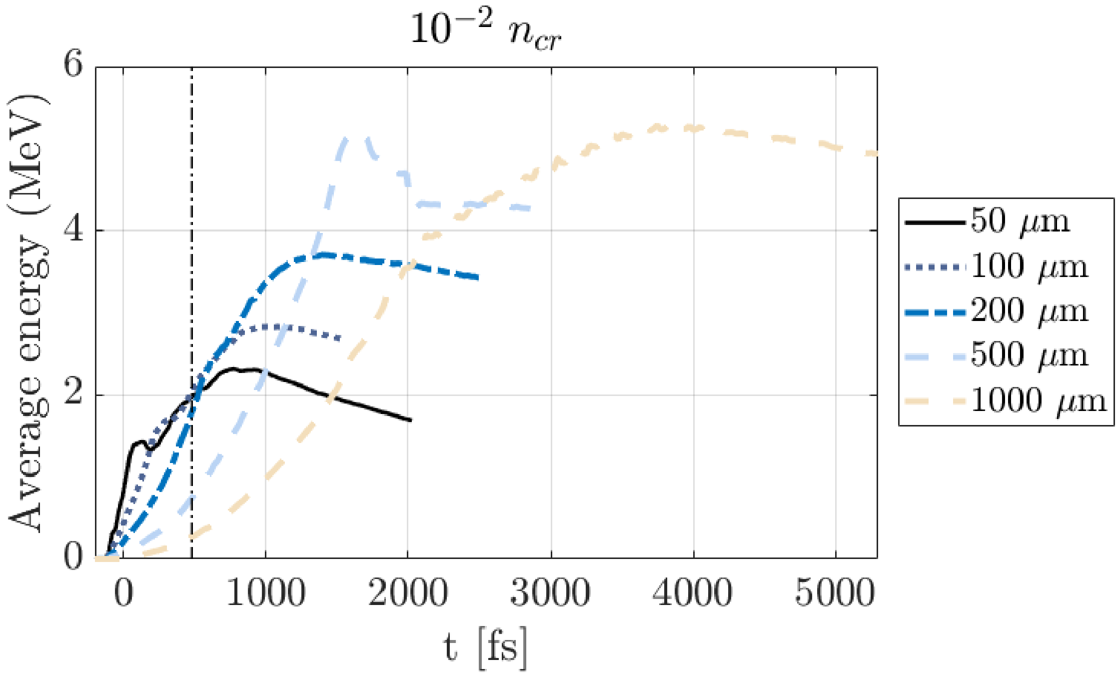
Heating is robust over $10^{-3} - 10^{-2}\ n_{cr}$, but breaks down for higher density



- **Lasers substantially modify density profile for $10^{-3}\ n_{cr}$, but this does not appear to affect spectrum**
- **At lower density (e.g. $10^{-4}\ n_{cr}$), have $\omega_p < \omega_c$, which changes dynamics (based on 1D simulations)**
- **At higher density, charge separation E visibly interrupts cyclotron rotation**

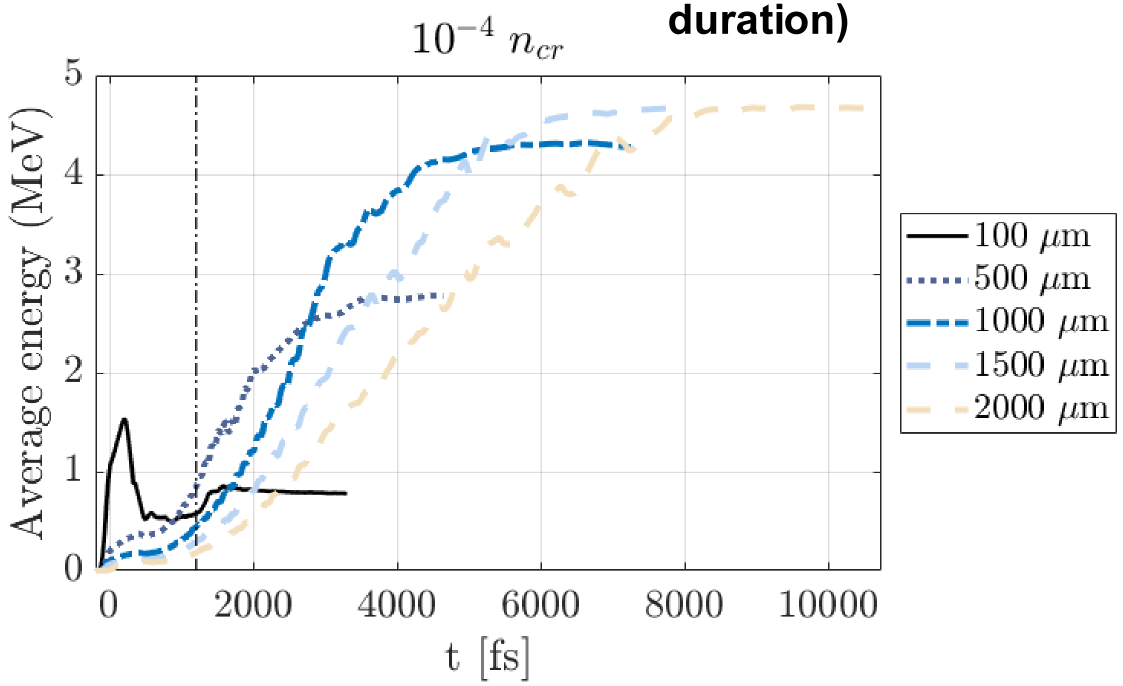
1D simulations predict even higher energy can be achieved in mm plasma, including with lower fields

$B_0 = 500$ T



$B_0 = 200$ T

(longer pulse duration)



Magnetically assisted DLA may be experimentally realizable using easily accessible plasma conditions