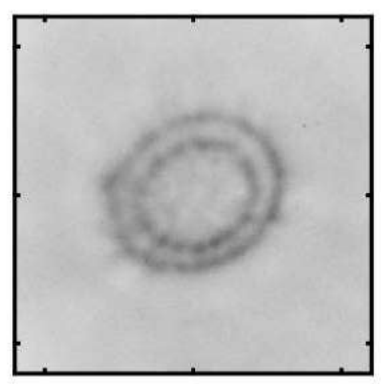
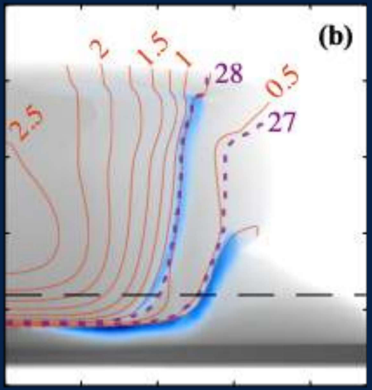
Magnetic signatures of radiation-driven double ablation fronts





P. T. Campbell, *et al*, PRL, 125, 145001 (2020)

Assistant Professor Louise Willingale

COLLEGE OF ENGINEERING
ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

LLNL Colloquium, 17th December 2020

Michigan Institute for Plasma Science and Engineering

A collaborative support organization for research, education and industrial interactions for plasma science and engineering

- **Focal point for university wide activities in plasmas and interactions with Federal agencies.**
- Opportunities for collaborative research across departments.
- Seed research activities to attract center-level funding.
- **Enhance graduate education in PSE.**
- Facilitate research with industry.
- Outreach to broader community.
- Discipline resource for career opportunities.

Director: Prof Mark Kushner

69+ faculty members from UM, MSU and more…

Activities

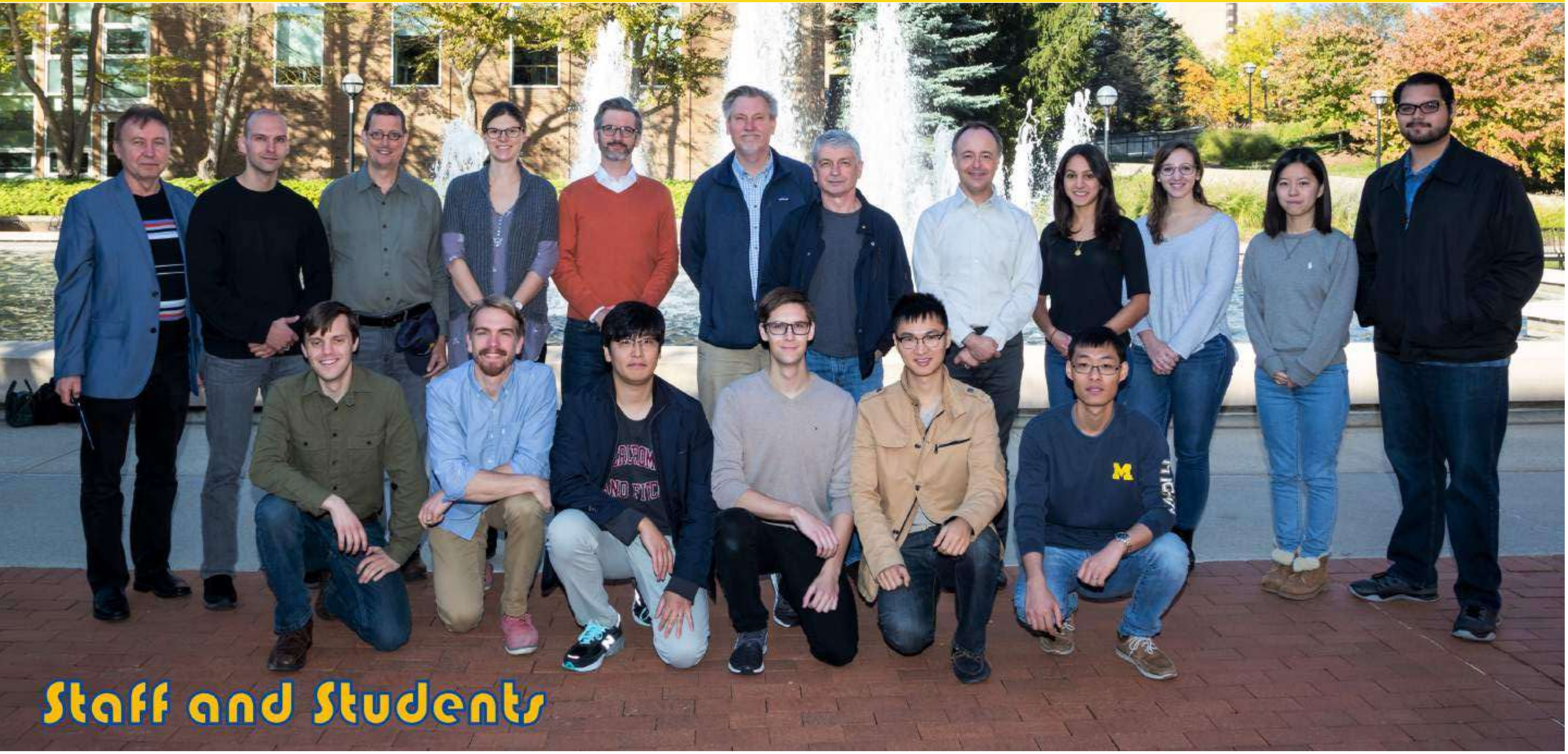
- **Seminar Series (also webcast)**
- Graduate Symposium
- **Graduate Certificate**
- Job Opportunities
- Outreach activities
- Plasmas in our Lives (video interviews of seminar speakers)
- Entry point for industrial interactions – many opportunities for engagement
- mipse-central@umich.edu

THE GÉRARD MOUROU
CENTER FOR ULTRAFAST OPTICAL SCIENCE
UNIVERSITY OF MICHIGAN

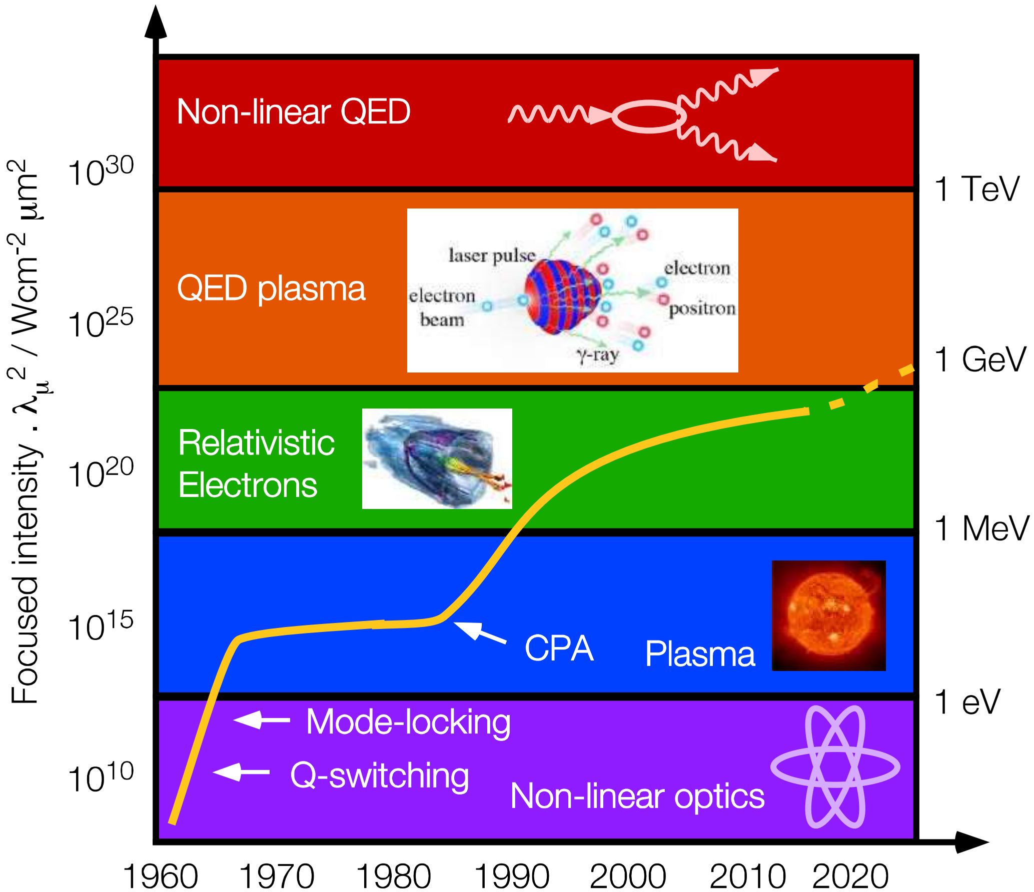
Personnel	Productivity
24 Faculty / PIs	$200M+ funding
250+ students	5000+ publications
1 Nobel Laureate	67 patents
	5 faculty startups

Interdisciplinary research center, 1990 → present

High Field Science group

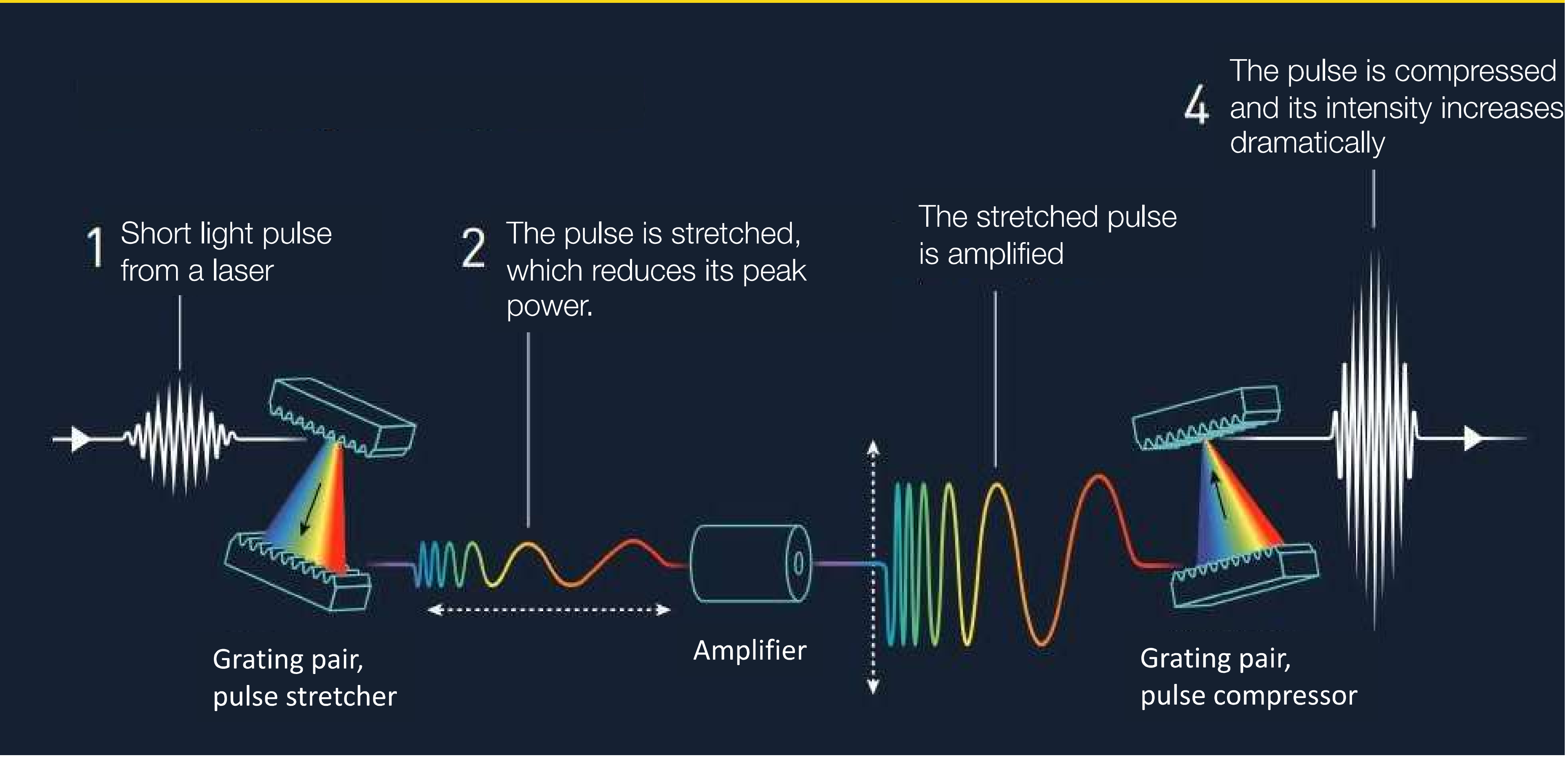


Focused laser conditions

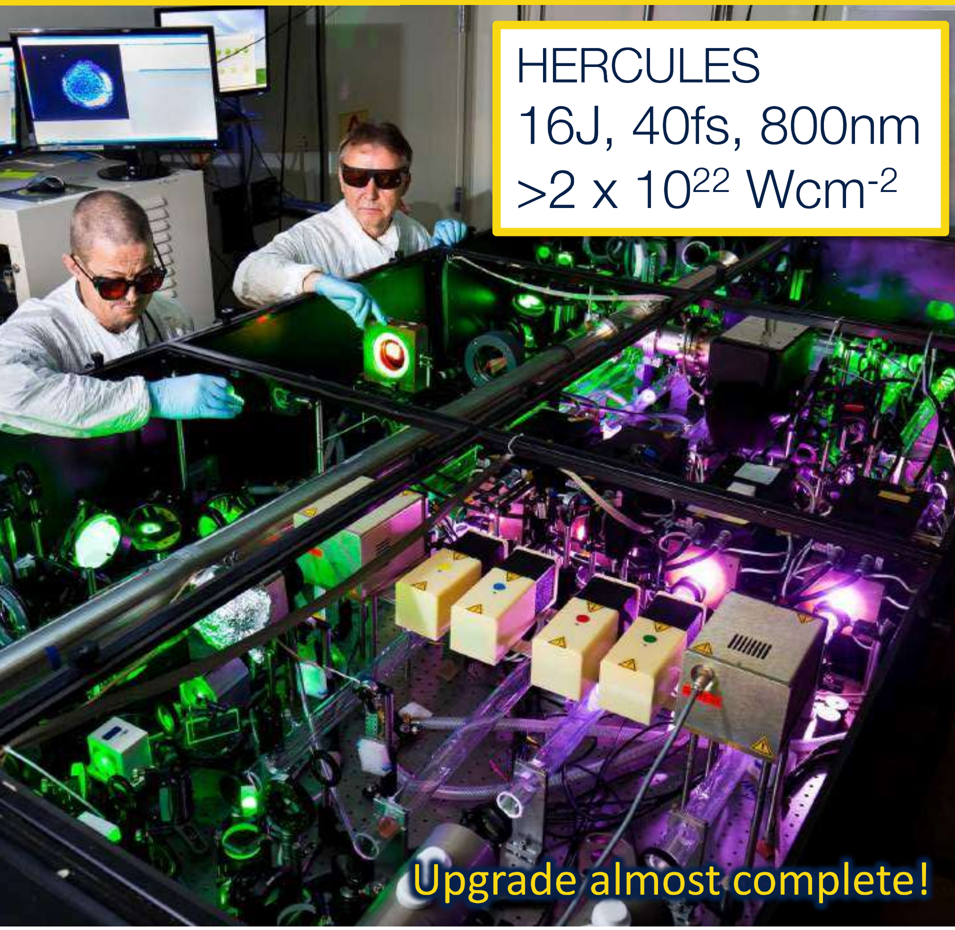


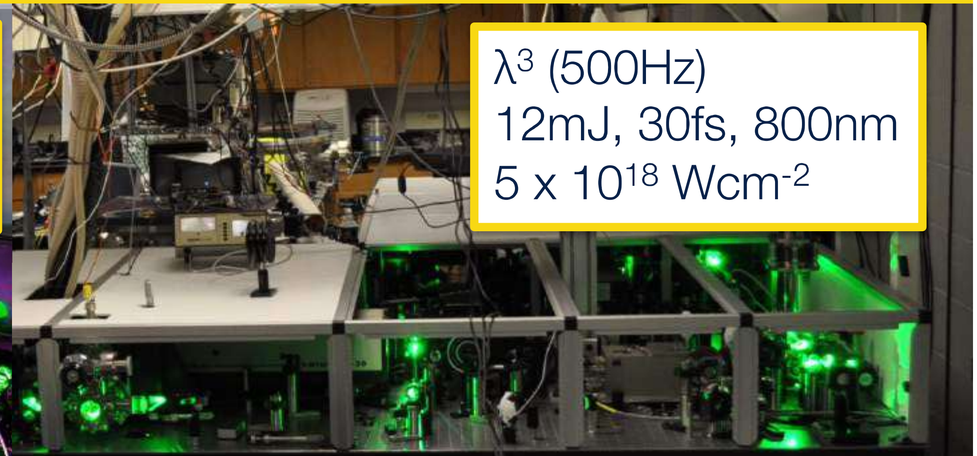
2018 Nobel prize for Physics awarded for CPA development

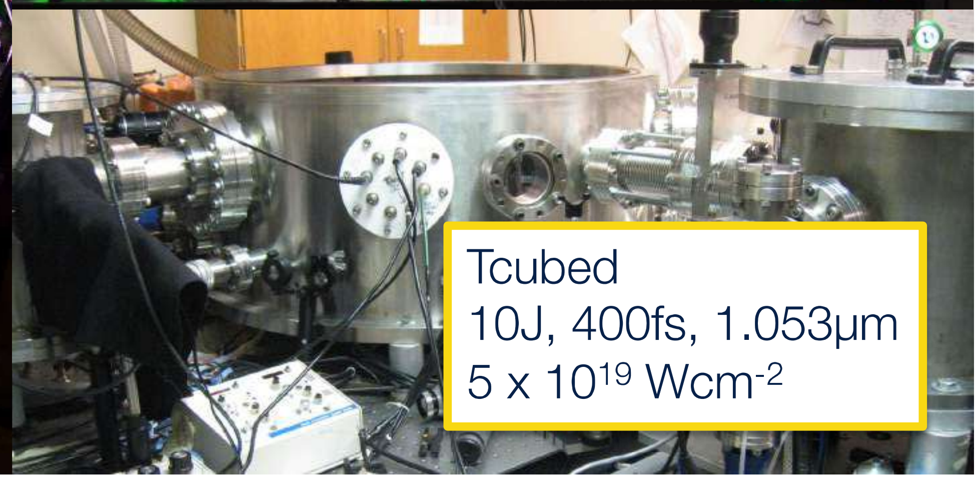
CPA - Chirped pulse amplification



HFS laser systems

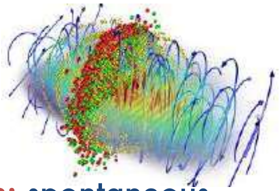






NSF has funded midscale research infrastructure (ZEUS) to access the QED-plasma regime in the laboratory

Electric field strength (V/m)



10^{20}

Vacuum breakdown: spontaneous creation of electron-positron pairs

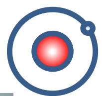
10^{15}

Current laboratory record

Electron accelerated to rest mass energy in 1 μm

10^{10}

Electric field of hydrogen ground state



10^{5}

10^{0}

Zettawatt = 10^{21} W

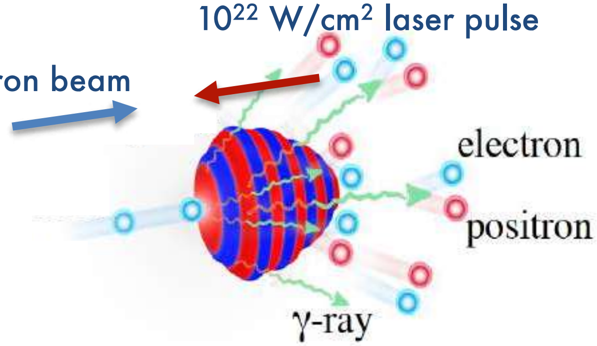
Equivalent Schwinger field $E_s \sim 10^{18}$ V/m

Ultrashort Laser

System

Actual power = 3 PW = 3 x 10^{15} W

In the rest frame of reference a GeV electron beam the intensity experienced will be equivalent to a Zettawatt power pulse!



Mid-scale Research – Award # 1935950

Approximate timeline

System design

Building construction

Laser assembly

Target area assembly

Commissioning experiments

NSF user facility
70% outside user time

2020 → 2021 → 2022 → 2023 → 2024

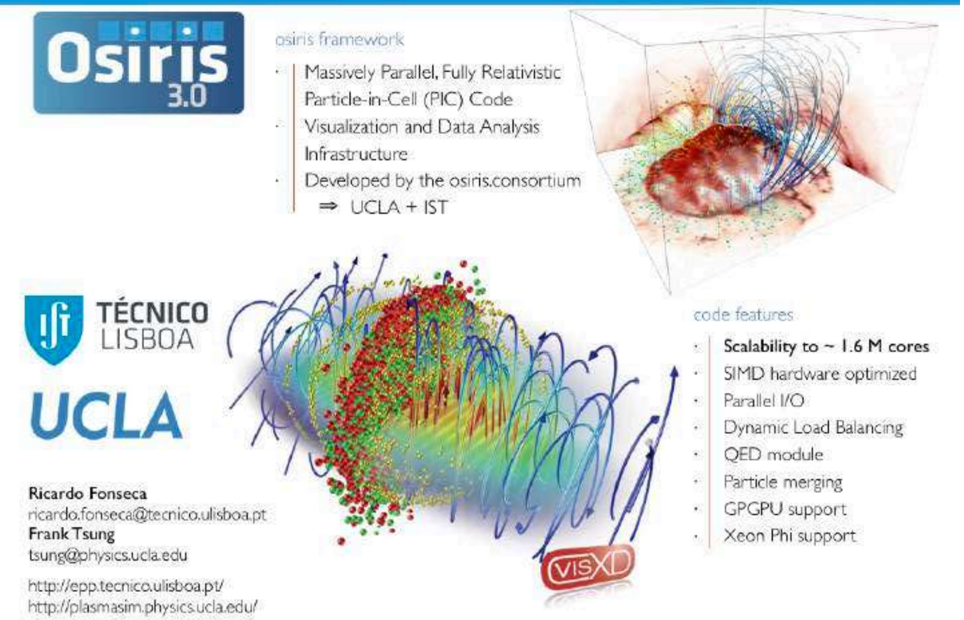
Upgraded Hercules operating →

Join the ZEUS user group: https://zeus.engin.umich.edu/users/

HFS numerical modeling capabilities

Particle-in-cell (PIC)

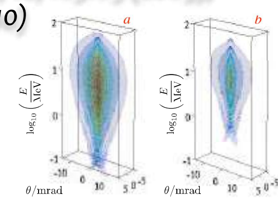
osiris 4.0



RTDX

*AGR Thomas & K Krushelnick, PoP, **16**, 103103 (2009);*
*AGR Thomas, PoP, **17**, 056708 (2010)*

3D radiation spectra calculations

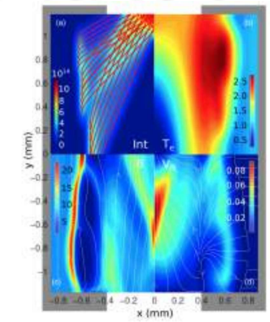


Vlasov-Fokker Planck (IMPACTA)

Study magnetic field generation and transport

*AGR Thomas et al, Journal of Computational Physics, **231**, 1051 (2011)*

*AGR Thomas et al, New Journal of Physics, **11**, 033001 (2009);*
*L Willingale et al, PRL, **105**, 095001 (2010);*
*L Willingale et al, PPCF, **53**, 124026 (2011);*
*A S Joglekar et al, PRL, **112**, 105004 (2014)*
*A S Joglekar et al, PRE, **93**, 043206 (2016)*

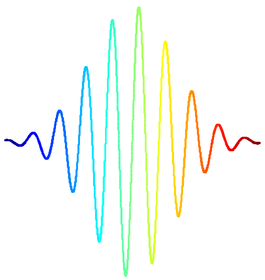


FIDO

Adapted to look at k-alpha production across a range of electron energies

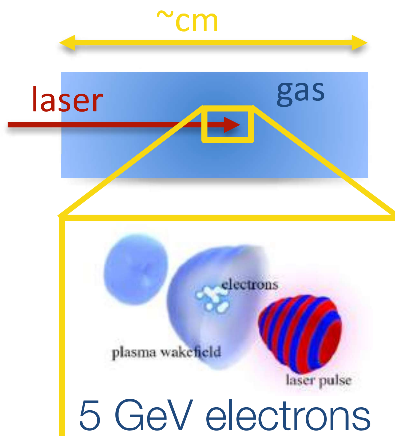
Why study high intensity laser-plasma interactions?

Light pulse



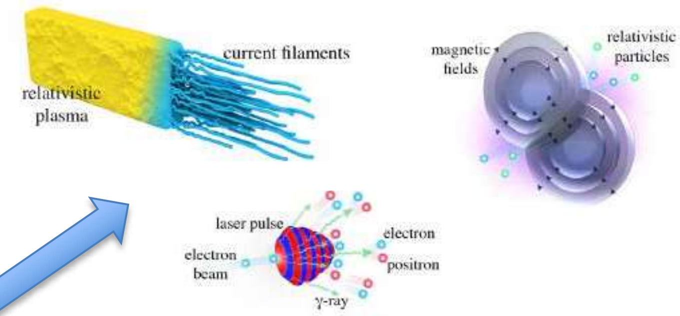
Our “Tool”

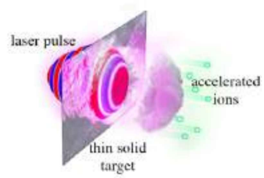
Miniaturize accelerators

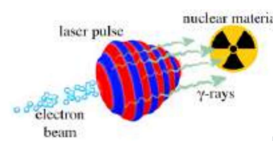


Unique, ultrashort, extremely bright particle & photon sources

Probing basic plasma physics







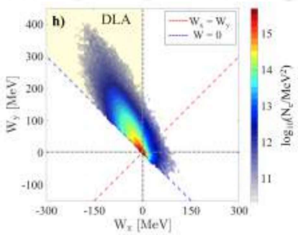
Broader applications..

Recent research

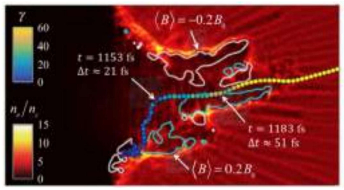
Electron heating across the density spectrum

Underdense Near-critical Overdense

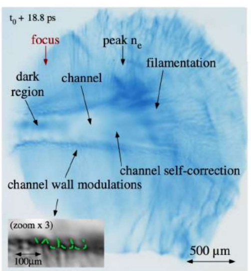
A Hussein, et al., submitted (2020)



L Willingale, et al., NJP, **20**, *093024 (2018)*



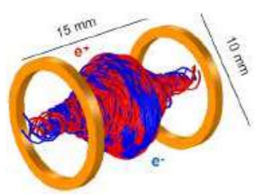
L Willingale, et al., NJP, **15**, *025023 (2013)*



Proton radiography

Pair plasma

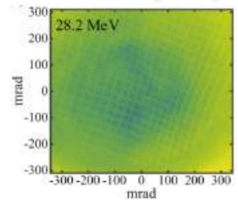
Hui Chen's group



Ion acceleration mechanisms

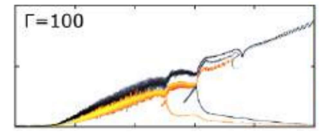
TNSA

PT Campbell, et al., NJP, **21**, *103021 (2019)*



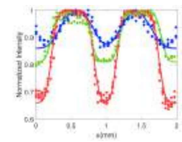
Shock driven

BK Russell, et al., in preparation (2020)



Detectors

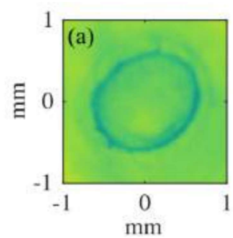
H Tang, et al., submitted(2020)



Magnetic fields

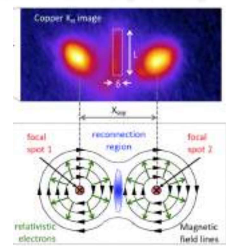
Generation

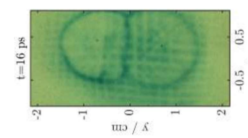
PT Campbell, et al., PRL, **125**, *145001 (2020)*



Reconnection

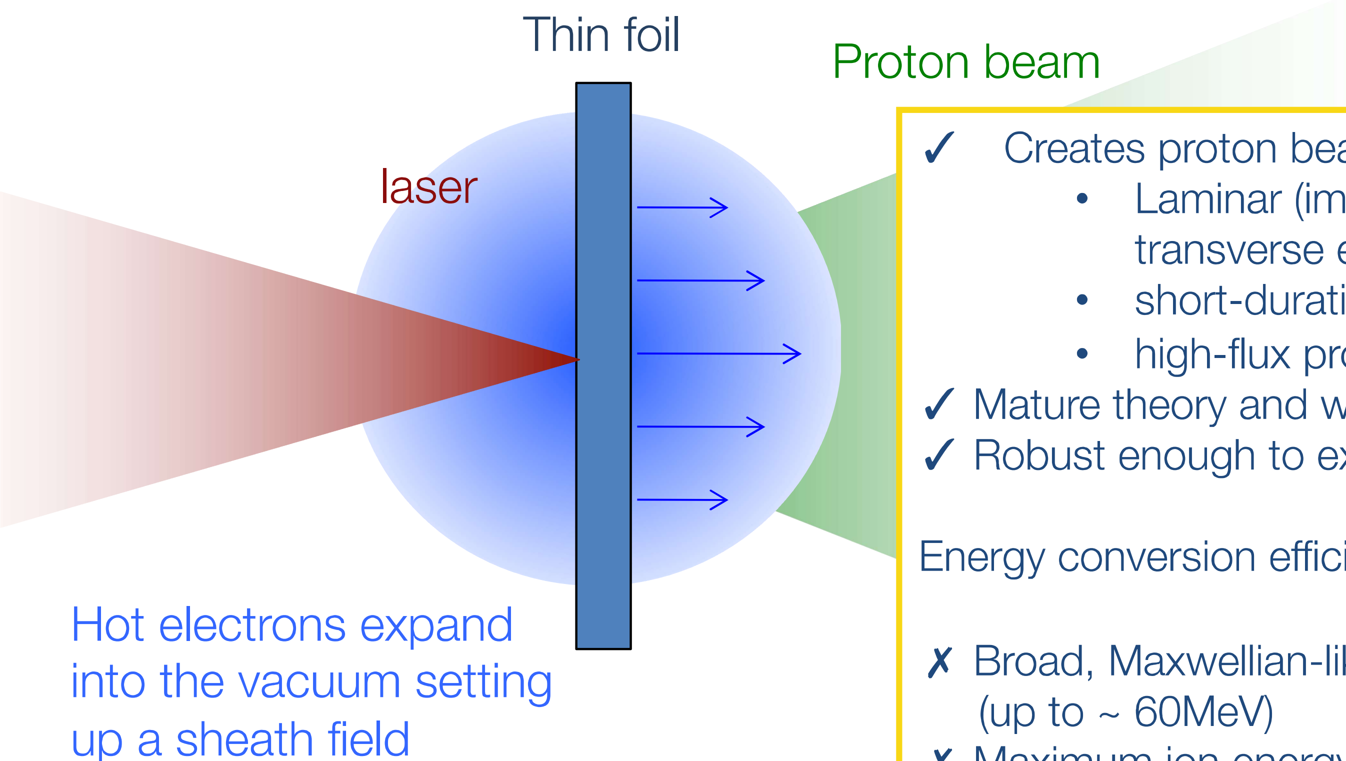
AE Raymond, et al., PRE, **98**, *0432073 (2018) ;*
CAJ Palmer, et al., PoP, **26**, 083109 (2019)





Target normal sheath acceleration (TNSA)

S Hatchett, et al, PoP, 7, 2076 (2000)

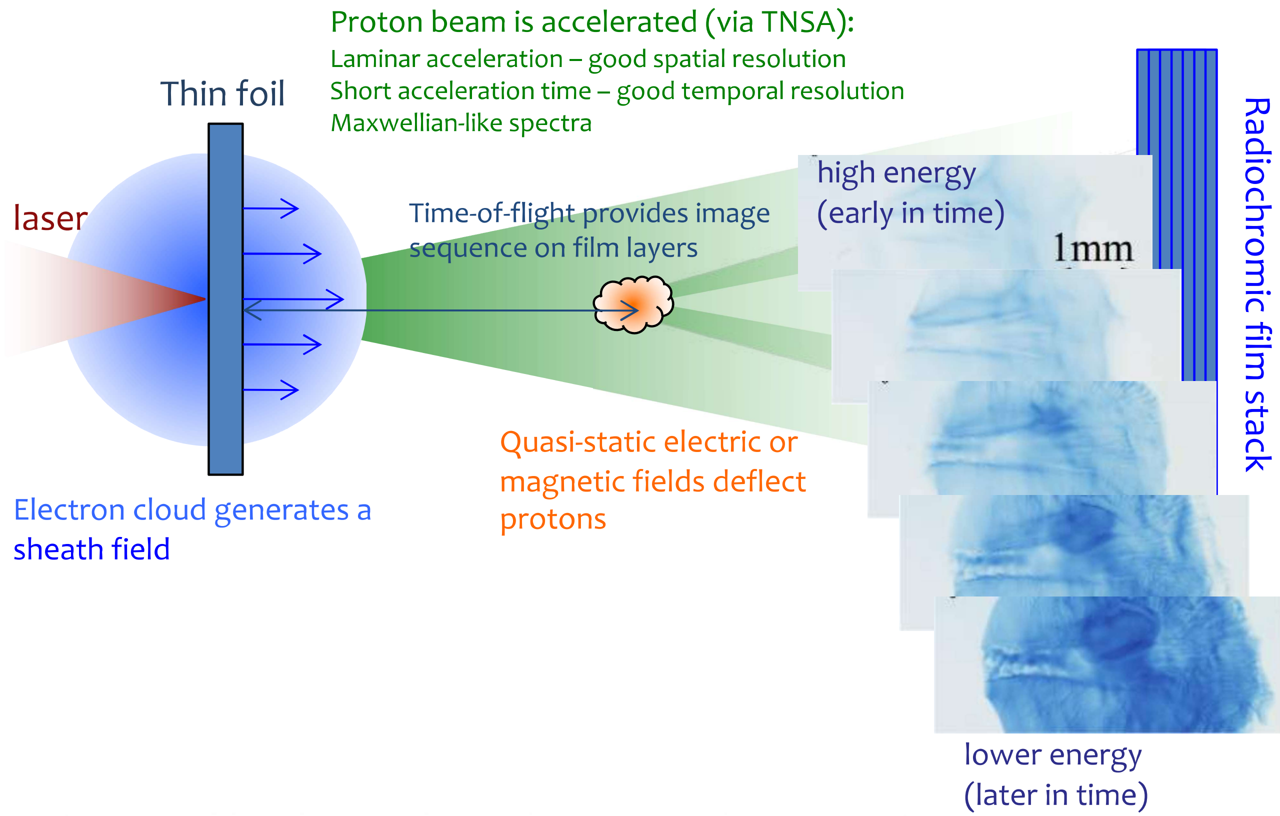


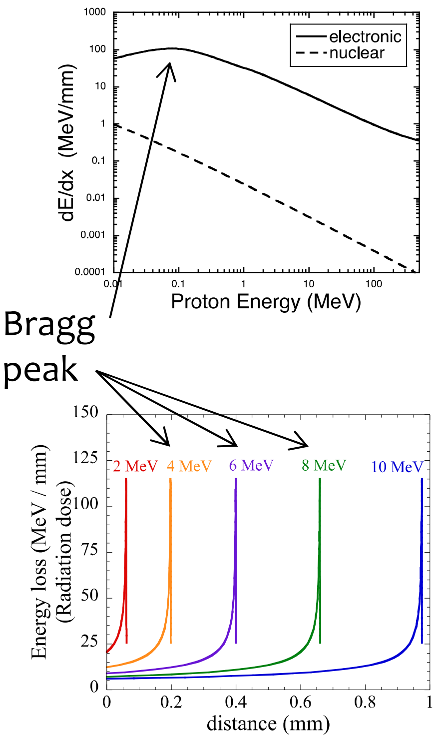
- ✓ Creates proton beams that are
  - Laminar (imaging quality ≥ 10 μm), transverse emittance < 0.004 mm mrad
  - short-duration (~picosecond at source)
  - high-flux proton beams (>10^{12} protons)
- ✓ Mature theory and well studied mechanism
- ✓ Robust enough to explore applications

Energy conversion efficiency ~ few %

- ✗ Broad, Maxwellian-like energy spread (up to ~ 60MeV)
- ✗ Maximum ion energy scale with laser energy

Application: Proton radiography

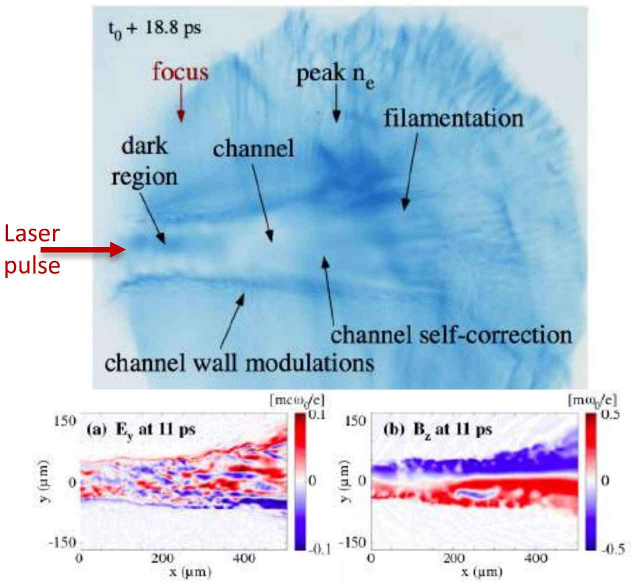




M Borghesi et al, Rev Sci Inst, 74, 1688 (2003); Laser and Part Beams, 20, 269 (2002)

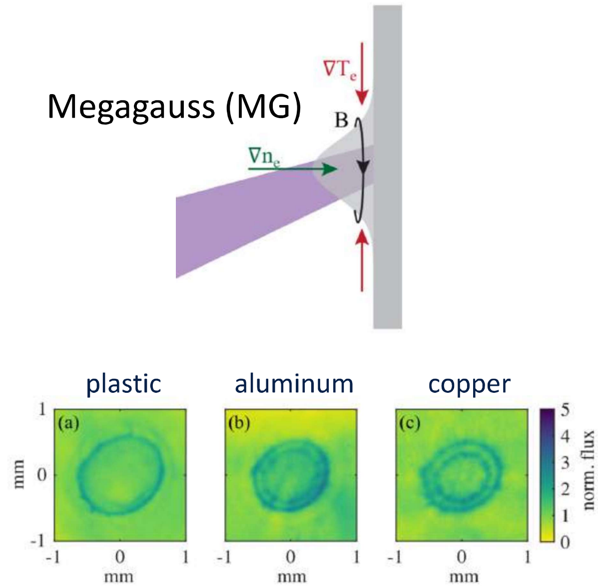
Imaging electromagnetic fields with protons

Channel formation



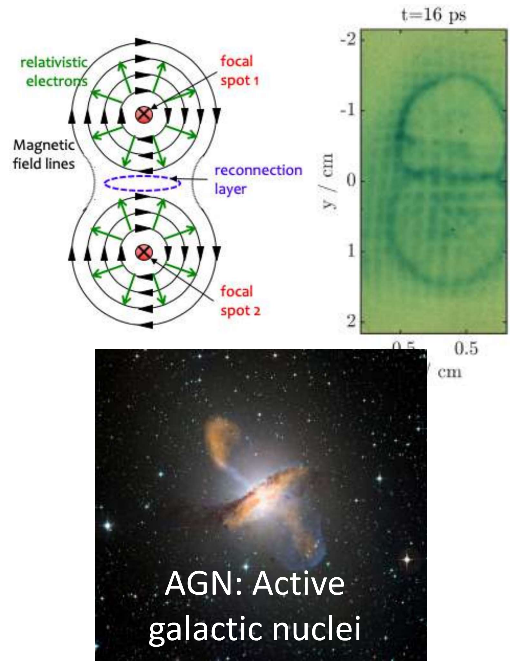
L Willingale, et al., PRL, 106, 105002 (2011)
L Willingale, et al., NJP, 15, 025023 (2013)

Magnetic field dynamics



P T Campbell, et al., PRL, 125, 145001 (2020)

Magnetic reconnection



CAJ Palmer, et al., PoP, 26, 083109 (2019)

Acknowledgements

Magnetic signatures of radiation-driven double ablation fronts

Paul T Campbell

Paul T Campbell, Brandon K Russell, Gennady Fiksel, Alec Thomas, Karl Krushelnick

Imperial College London

Christopher A Walsh*, Aidan Crilly, Jerry P Chittenden

UR LLE

Phillip Nilson

* Now at LLNL!

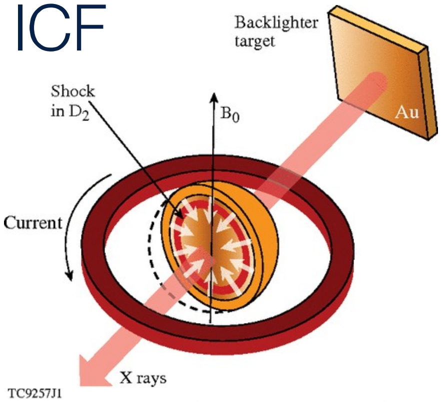
NSF NLUF

This material is based upon work supported by the Department of Energy, National Nuclear Security Administration under Award Numbers DE-NA0003606 and DE-NA0003764. PTC is supported by the U.S. Department of Energy Fusion Energy Sciences Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-SC0014664. BKR acknowledges support from NSF Award Number 175142.

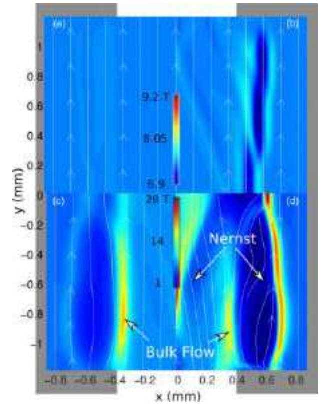
Simulation results reported in this paper were obtained using the Imperial College High Performance Computer Cx1.

Magnetic fields in plasmas can strongly influence the dynamics and are important in many HEDP laboratory and astrophysical plasmas

ICF

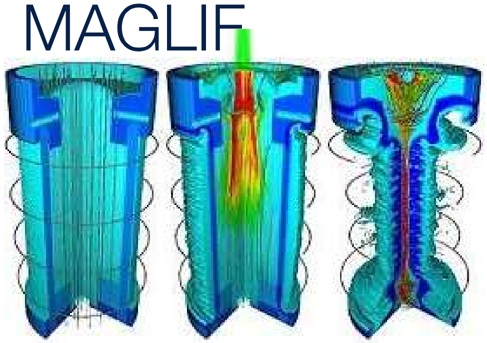


PY Chang, et al., PRL, 107, 035006 (2011)

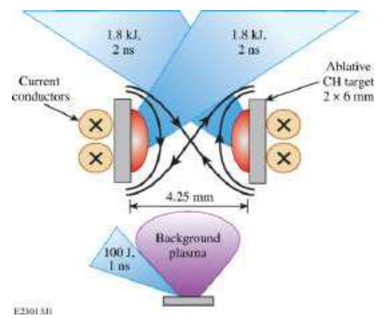


A Joglekar, et al., PRE, 93, 043206 (2016)

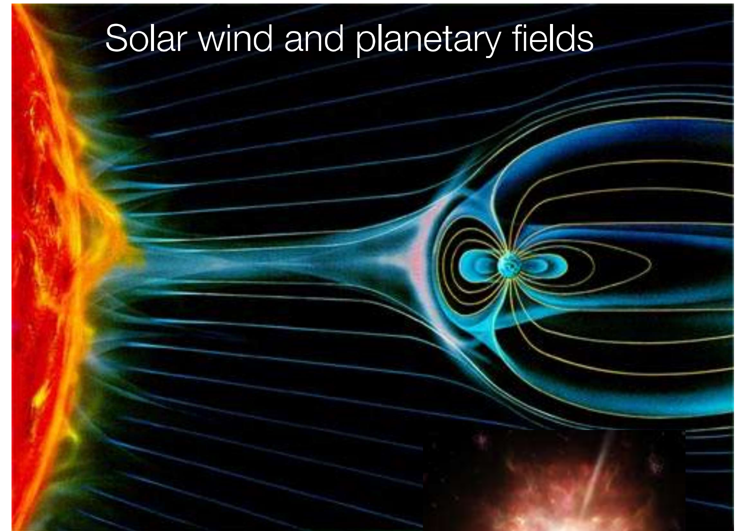
MAGLIF



SA Slutz, et al., PoP, 17, 056303 (2010)



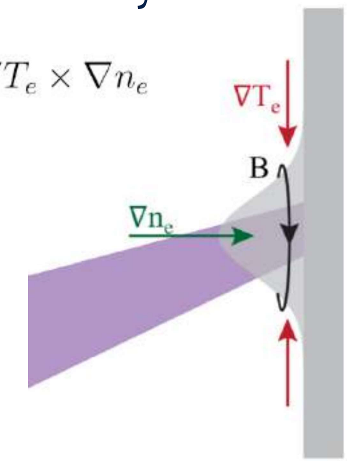
G Fiksel, et al., PRL, 113, 105003 (2014)



Laser generated magnetic fields and reconnection have previously been studied using nanosecond laser pulses

Biermann Battery effect:

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{k_B}{e n_e} \nabla T_e \times \nabla n_e$$



Nanosecond laser pulses

$I \sim 10^{14}$ Wcm^{-2}

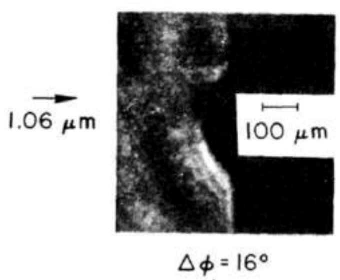
$B \sim 1$ MG

$v_B \sim 10^5$ ms^{-1}

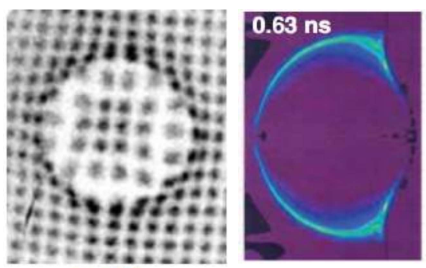
$\beta \sim 10 - 100$

Magnetic reconnection

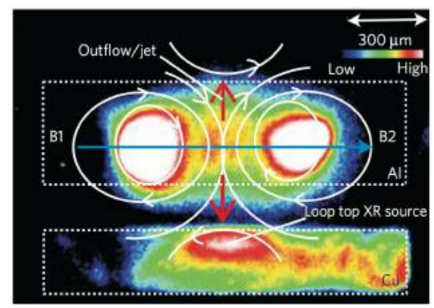
PM Nilson, et al., PRL, 97, 255001 (2006)



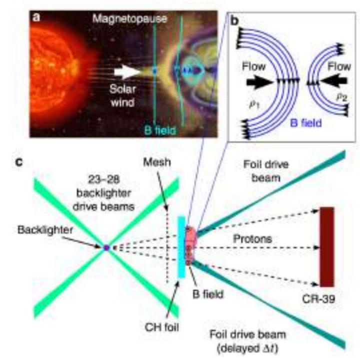
JA Stamper and BH Ripen, PRL, 34, 138 (1975)



CK Li, et al., PRL, 97, 255001 (2006)

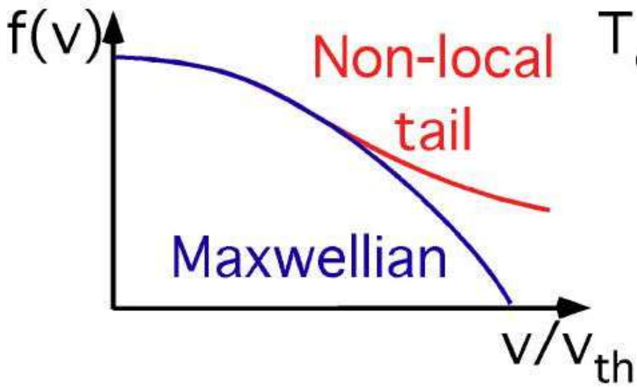


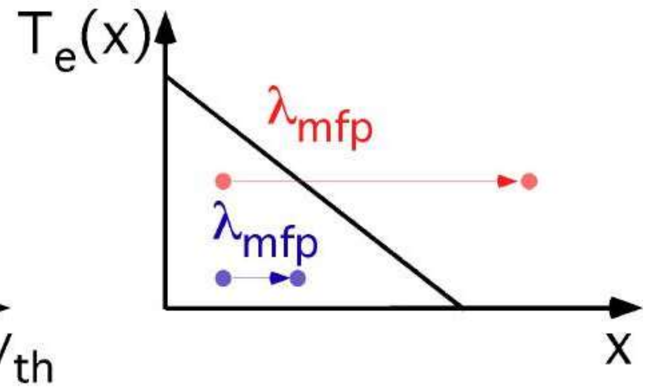
J Zhong, et al., Nature Physics, 6, 984 (2010)

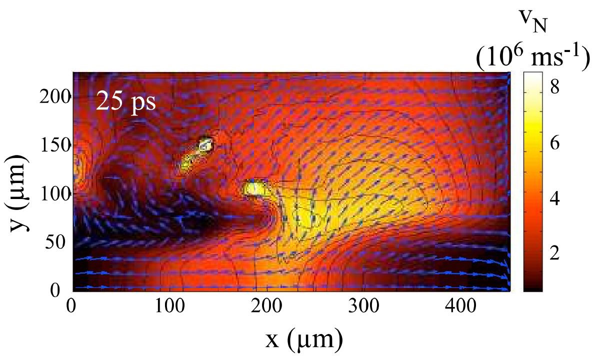


MJ Rosenberg, et al., Nature Comms, 6, 6190 (2015)

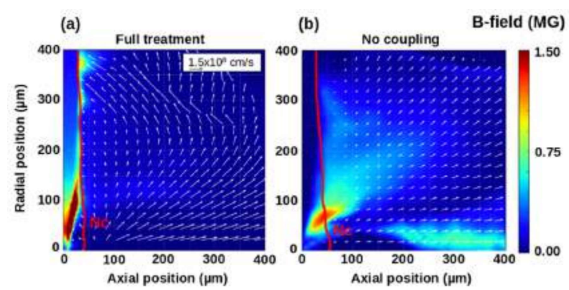
The magnetic fields can travel faster than the ion fluid velocity at the Nernst velocity (with the heat flow) in a hot plasma



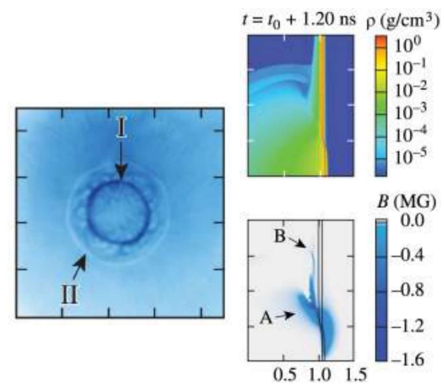




L Willingale et al., PRL, 105, 095001 (2010)



L Lancia, et al., PRL, 113, 235001 (2014)

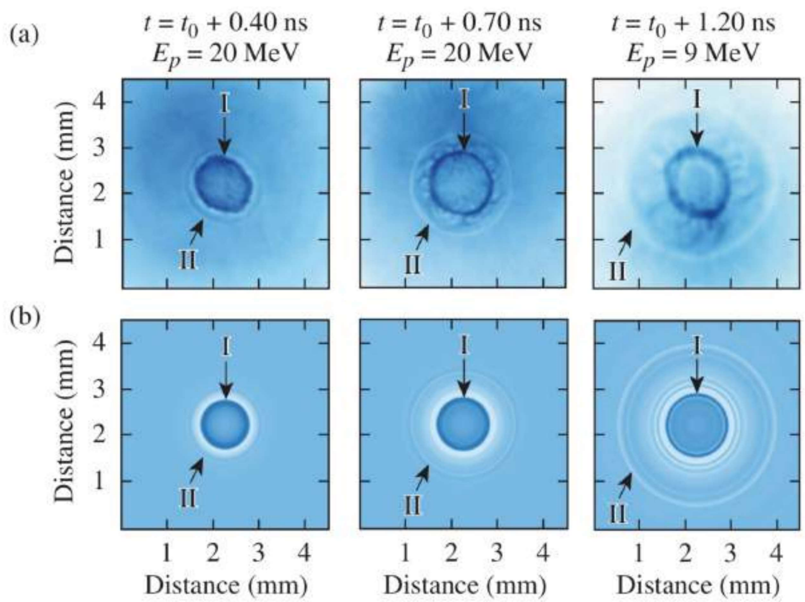


L Gao, et al., PRL, 114, 215003 (2015)

Previous work by Gao et al, used proton radiography to observe the magnetic field evolution from a CH target

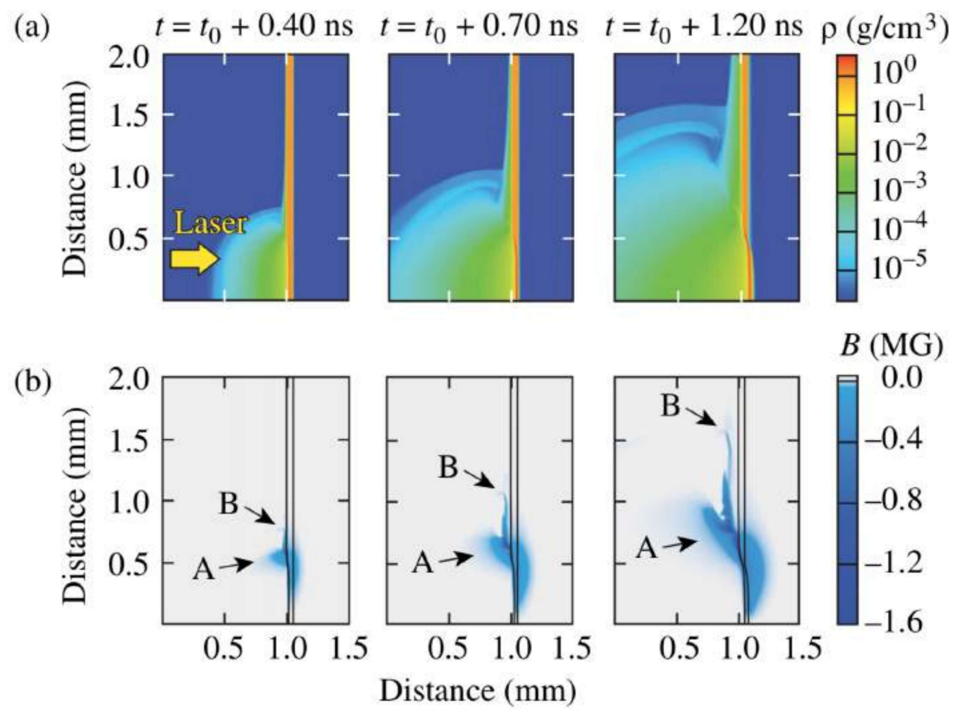
L Gao et al., PRL, 114, 215003 (2015)

Experimental proton radiographs



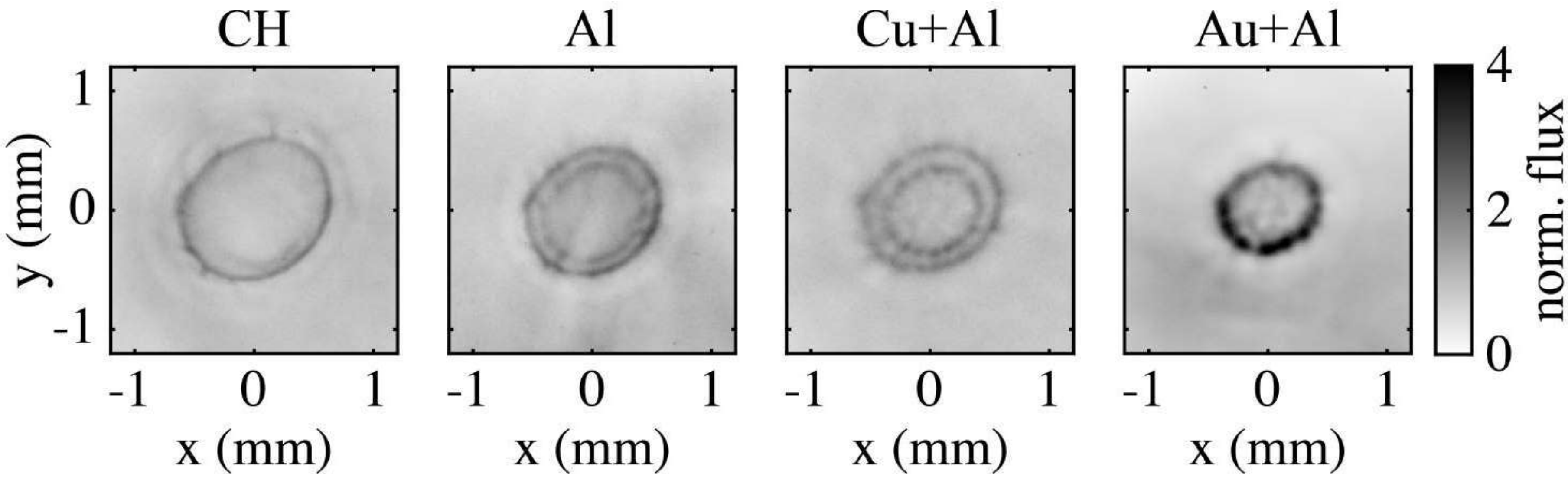
Modeled proton radiographs

DRACO modeling

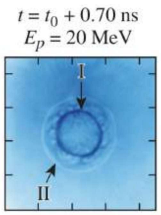


Proton radiographs: Varying the target material

Proton radiographs at 0.75 ns



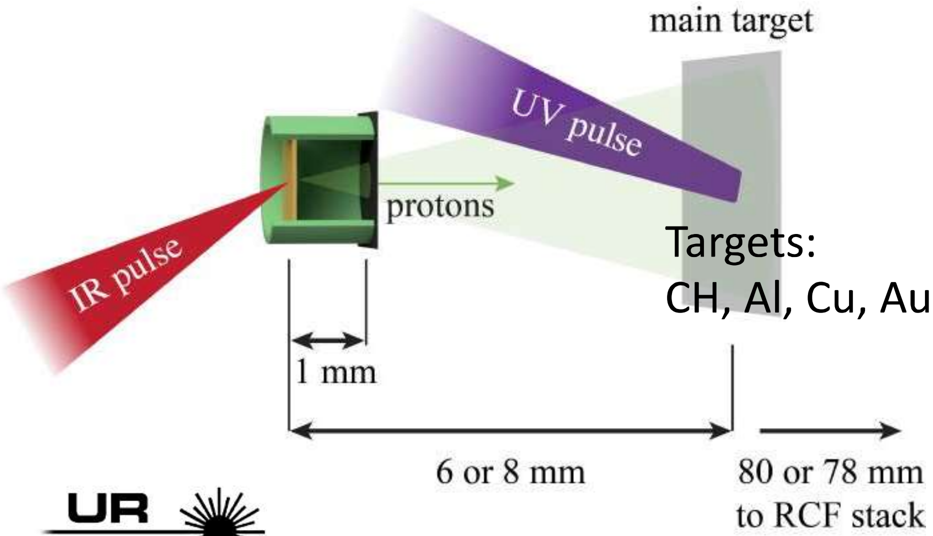
c.f. L Gao et al., PRL, 114, 215003 (2015)



OMEGA EP experiment and Gorgon modeling setup

UV pulse parameters:

1250 J, 1 ns square temporal profile
820 μm diameter super-Gaussian spot
peak intensity of $(2.2 \pm 0.07) \times 10^{14}$ Wcm^{-2}



Targets:
CH, Al, Cu, Au

UR LLE

Gorgon*:

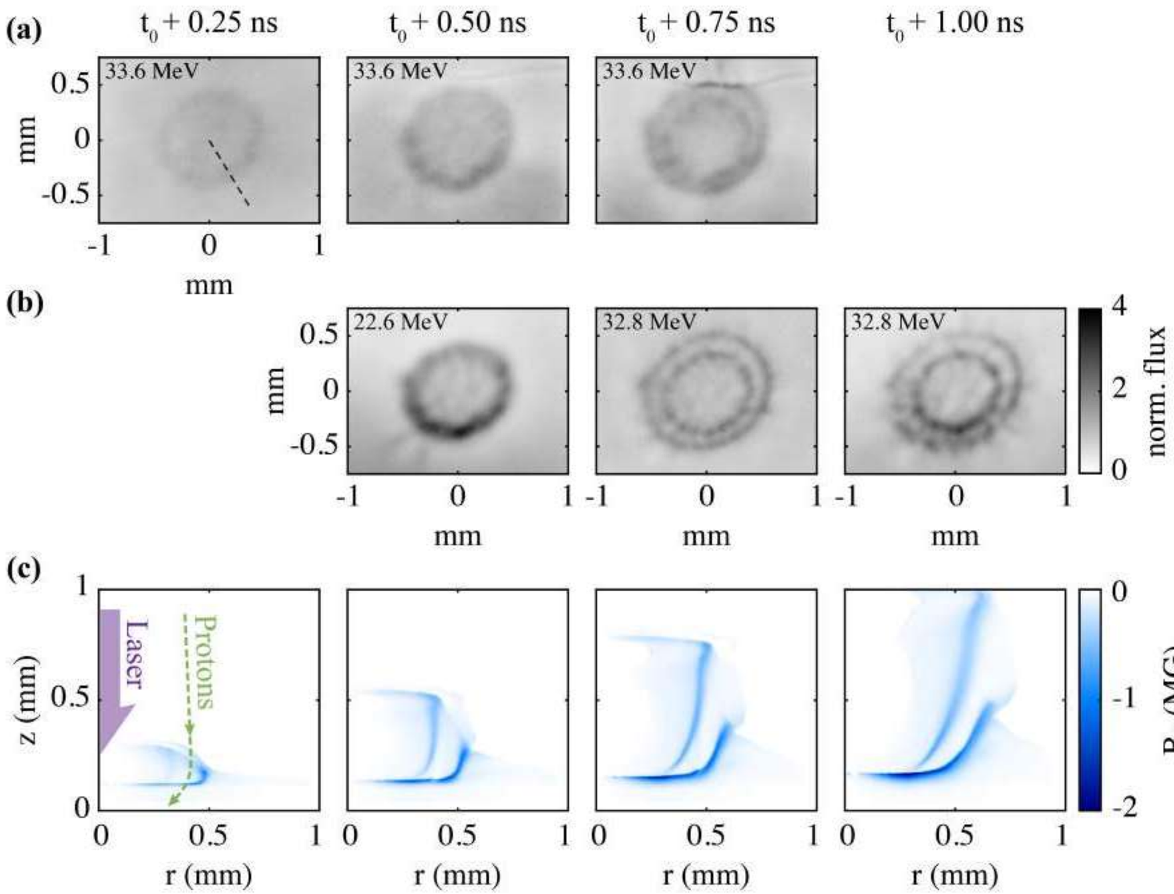
Extended-magnetohydrodynamics (MHD) code and includes:

- magnetic transport from bulk plasma flow
- Laser: Ray-tracing w/ inverse Bremsstrahlung heating
- Nernst
- cross-gradient-Nernst
- resistive diffusion
- Biermann Battery generation

*C. A. Walsh, J. P. Chittenden, K. McGlinchey, N. P. L. Niasse, and B. D. Appelbe, PRL, 118, 155001 (2017).

Imperial College London

Copper target proton radiographs

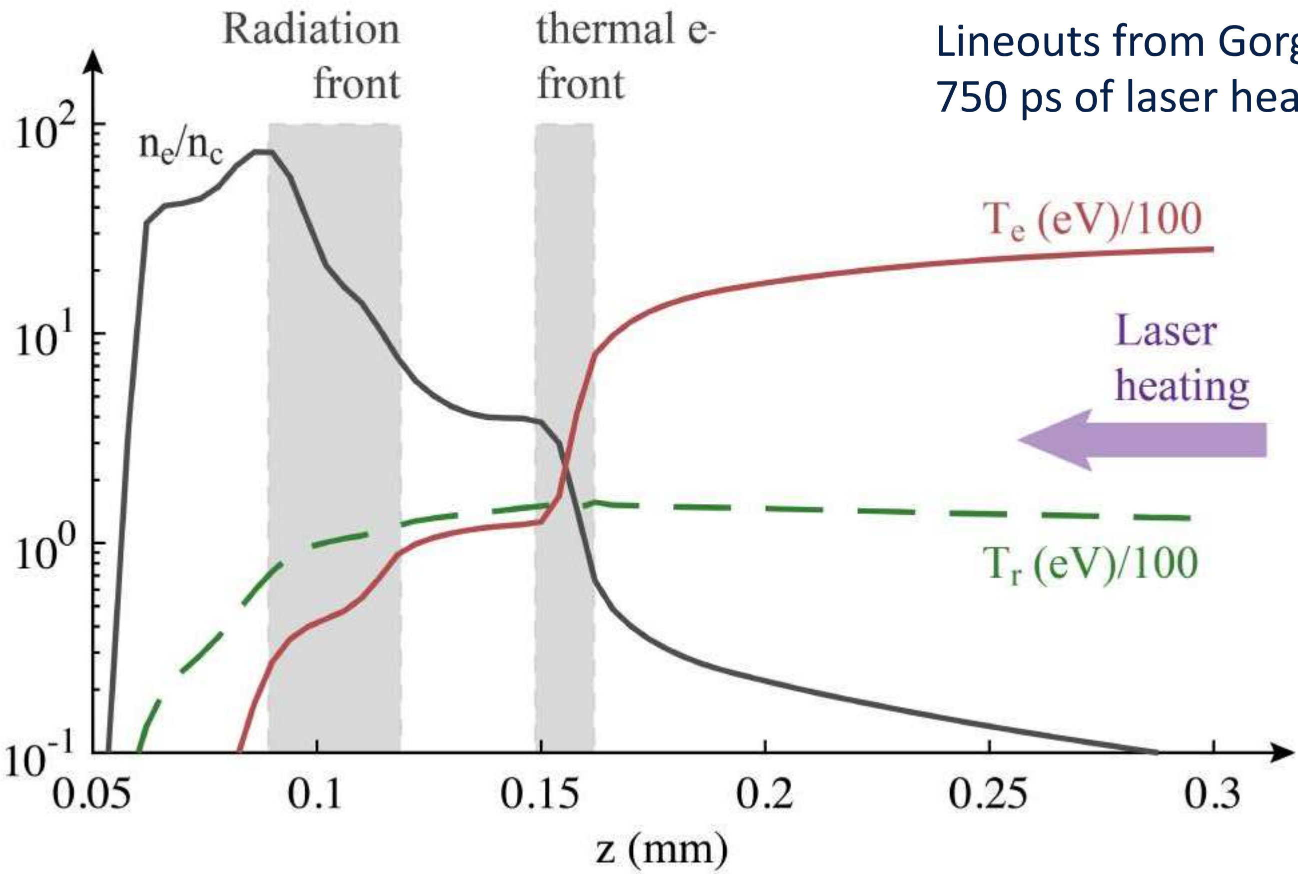


25 μm copper

1 μm copper on 50μm aluminum

Gorgon simulation of copper

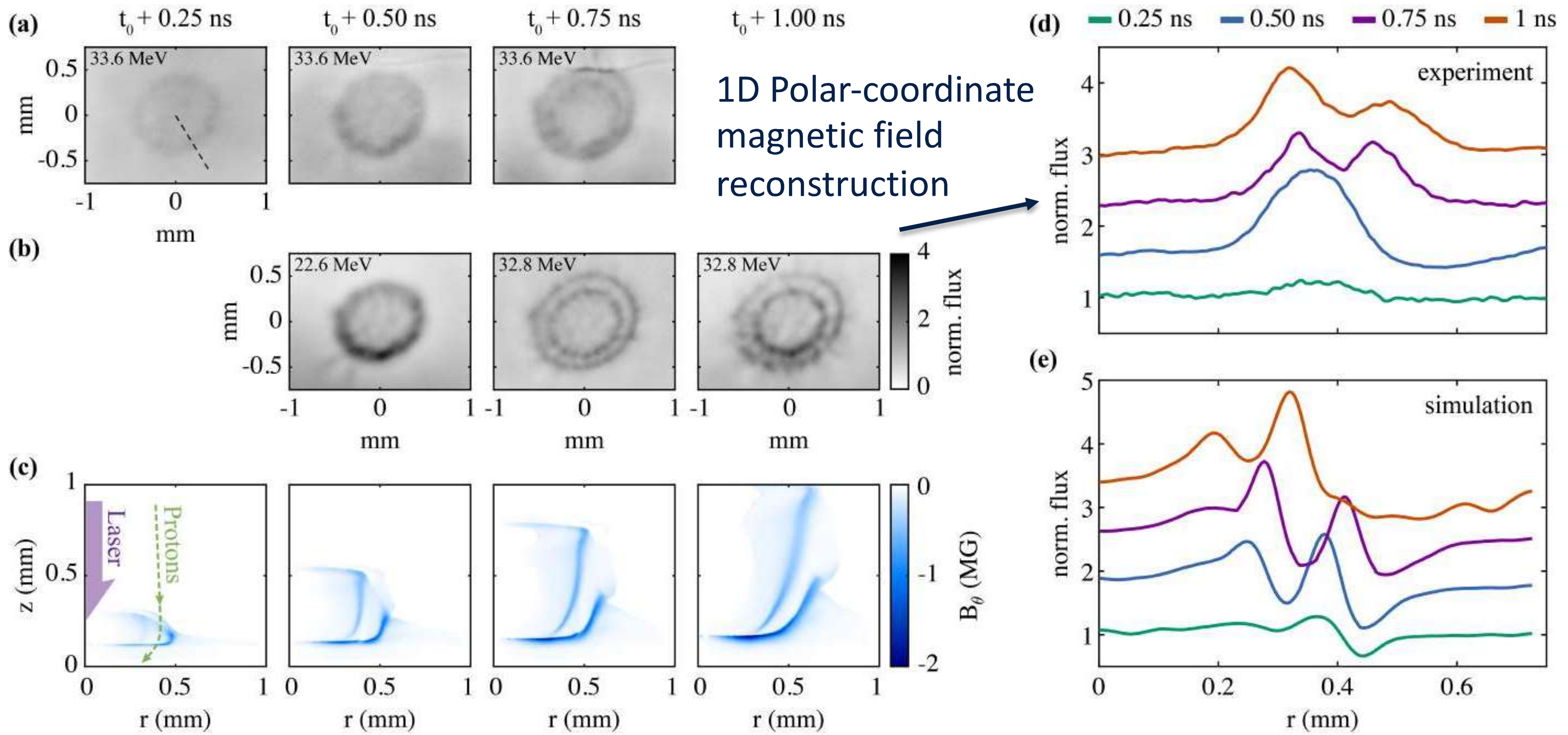
Double ablation fronts (DAFs)



Lineouts from Gorgon, along laser axis after 750 ps of laser heating, Cu target

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{k_B}{e n_e} \nabla T_e \times \nabla n_e$$

Copper target proton radiographs



1D Polar-coordinate magnetic field reconstruction

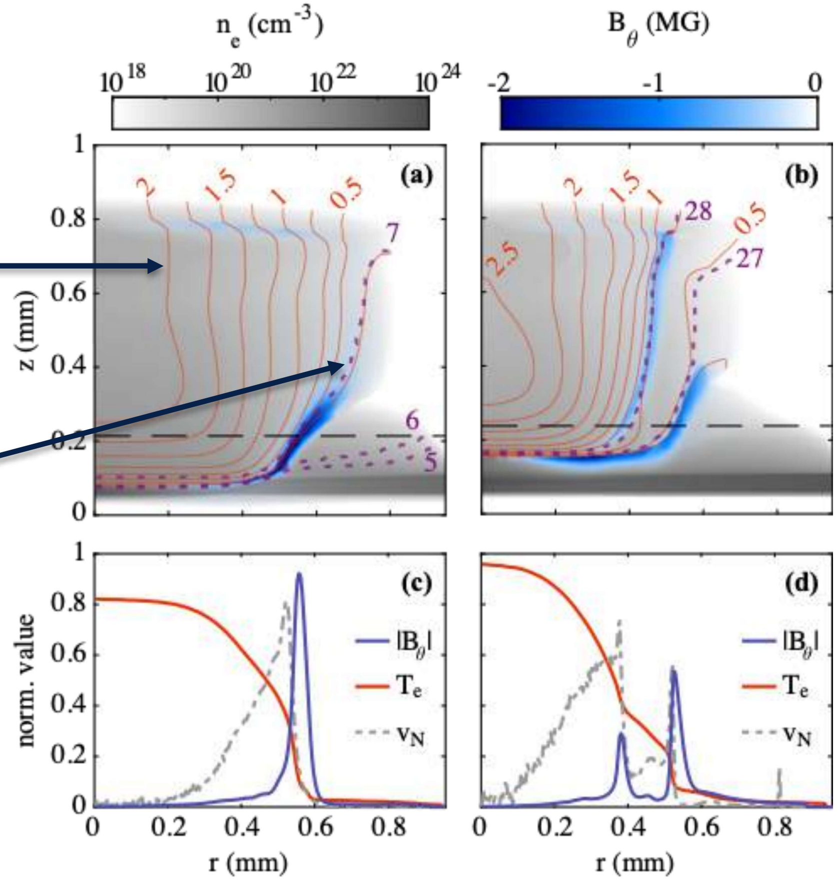
Gorgon simulations:
Difference between Plastic and Copper targets (at t_0 + 0.75 ns)

CH

Cu

Electron temperature contours

Effective ionization states



Suppression of Biermann Battery magnetic field generation

M. Sherlock and J. J. Bissell, PRL, 124, 055001 (2020): "Classical models substantially overestimate the importance of magnetic fields generated by the Biermann battery"

t = 0.75 ns

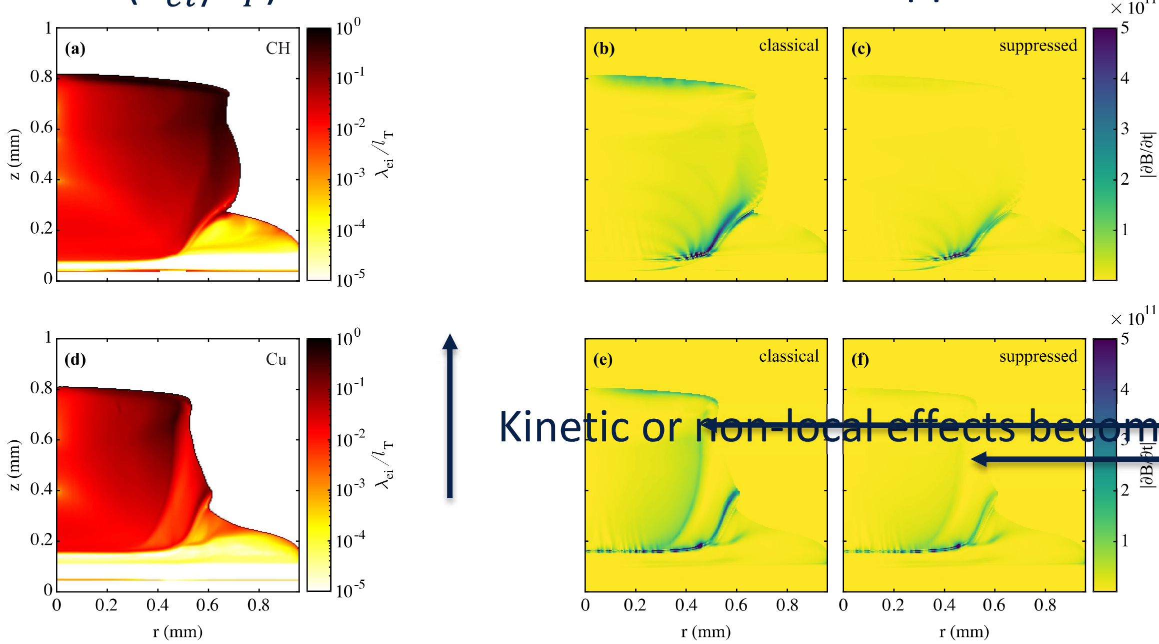
Knudsen number (λ_{ei}/l_T)

(Instantaneous) B-field generation rates

Classical Suppressed

CH

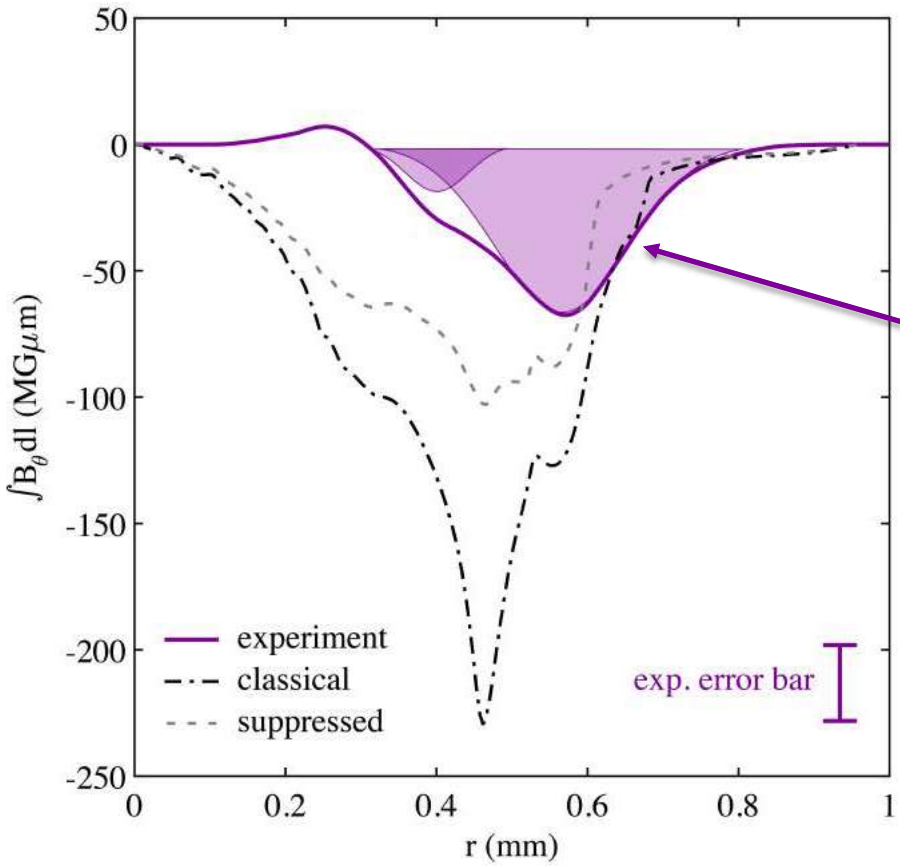
Cu



Kinetic or non-local effects become more significant

Inner ring particularly suppressed

Suppression of Biermann Battery magnetic field generation

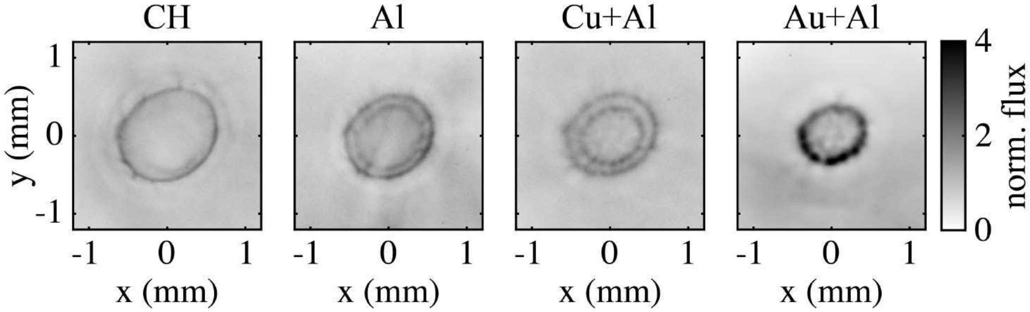


From the Cu target

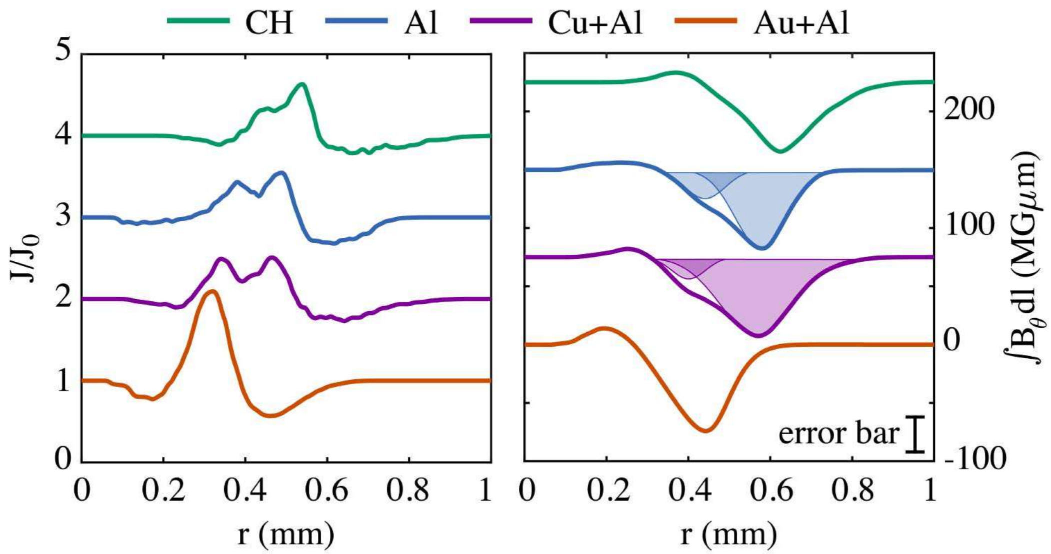
Double Gaussian fit to the experimental data

Proton radiographs: Varying the target material

Proton radiographs at 0.75 ns



Radial lineouts of the normalized proton flux



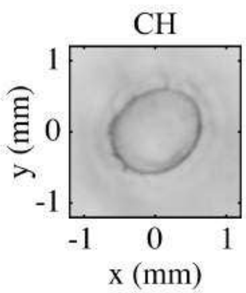
Path integrated magnetic field (performing a 1D polar-coordinate inversion on the proton flux)

Can we learn more?

M. Sherlock and J. J. Bissell, PRL, 124, 055001 (2020):

$$\frac{\partial B}{\partial t} \approx 0.083 \left(\frac{\lambda_{ei}}{l_T}\right)^{-0.453} \left(\frac{\partial B}{\partial t}\right)_{\text{classical}}$$

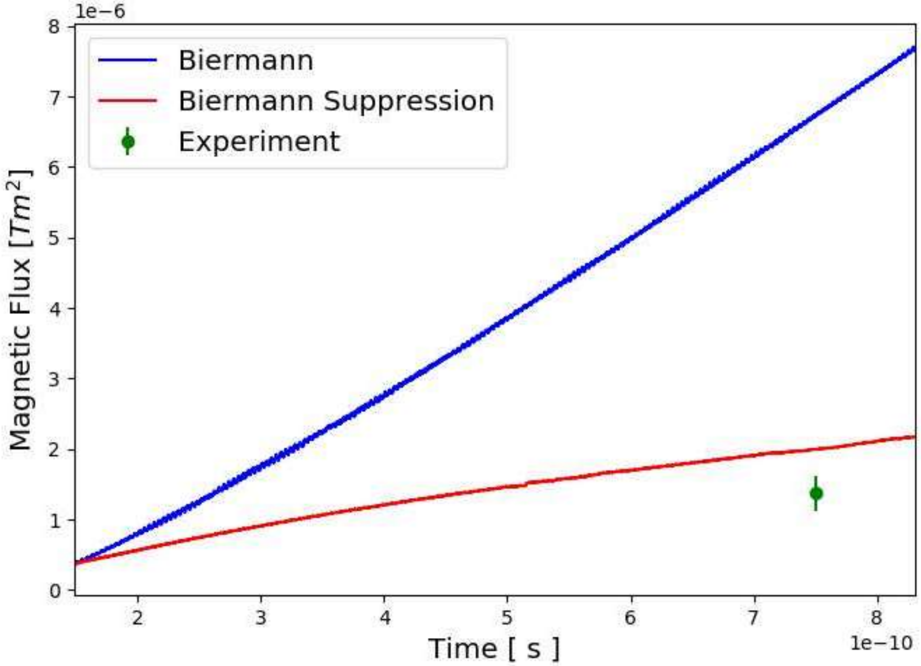
Take lineout through proton radiograph and assume small angle deflections to get the magnetic flux



Approximate laser intensity:

Planar foil:	2×10^{14} W/cm^2
OMEGA:	4×10^{14} W/cm^2
NIF PDD:	4×10^{14} W/cm^2

Gorgon run with and without Biermann suppression for CH



Matter and Radiation at Extremes

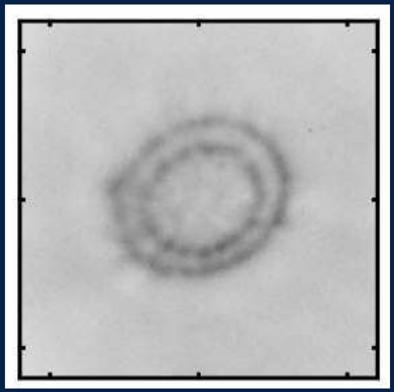
Special edition on “Magnetized Plasmas in HEDP”

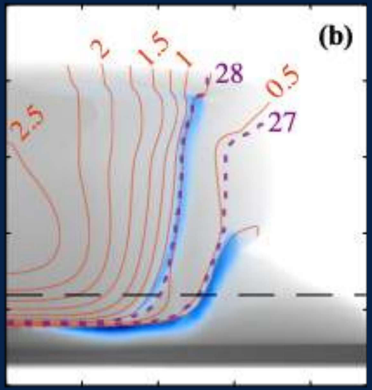
- Submission deadline 31st March 2021
- Guest editors:
  - Mario Manuel, General Atomics, United States
  - Sergey Lebedev, Imperial College London, England
  - Shinsuke Fujioka, Osaka University, Japan

Topics covered include, but are not limited to:

- High energy density plasma
- Magnetic field
- Hydrodynamic and kinetic instability
- Radiation driven inertial confinement fusion
- Magnetized liner fusion
- Laboratory astrophysics

Magnetic signatures of radiation-driven double ablation fronts





P. T. Campbell, *et al*, PRL, 125, 145001 (2020)

Assistant Professor Louise Willingale

COLLEGE OF ENGINEERING
ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

LLNL Colloquium, 17th December 2020

MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN

Gorgon/ Chimera code

C. A. Walsh, J. P. Chittenden, K. McGlinchey, N. P. L. Niasse, and B. D. Appelbe, PRL, 118, 155001 (2017).

Imperial College London

3D Cartesian, Cylindrical & Spherical geometry

Extended MHD capabilities:Generalized Ohm's Law -Biermann battery, Nernst, cross-Nernst, electron inertia (different solver)

Magnetised Heat Flow - anisotropic heat flow (super-stepping), Righi-Leduc, Ettinghausen.
Spitzer/Braginskii conductivity models or Lee-More-Desjarlais / Sesame table interface

Multi-group explicit P1/3 automatic flux limited radiation transport.
Radiation and atomic data from in house CRE, DCA code 'Spk'. Laser ray tracing.

Magnetized Monte Carlo fast particle and alpha-burn package with different stopping models (Spitzer, Maynard-Deutsch-Zimmerman) and dynamic population management.

Full stress tensor & Johnson Cook material strength model
two temperature (electrons and ions) Equation of State with options for:

- Thomas-Fermi model or FEoS/Sesame file interface
- CAD file import, simple circuit models, SLIC & level-set based interface tackers, etc.