

Title: Experimental plasma physics

Date: Mar 16, 2016 11:00 AM

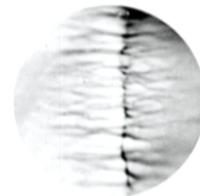
URL: <http://pirsa.org/16030106>

Abstract:

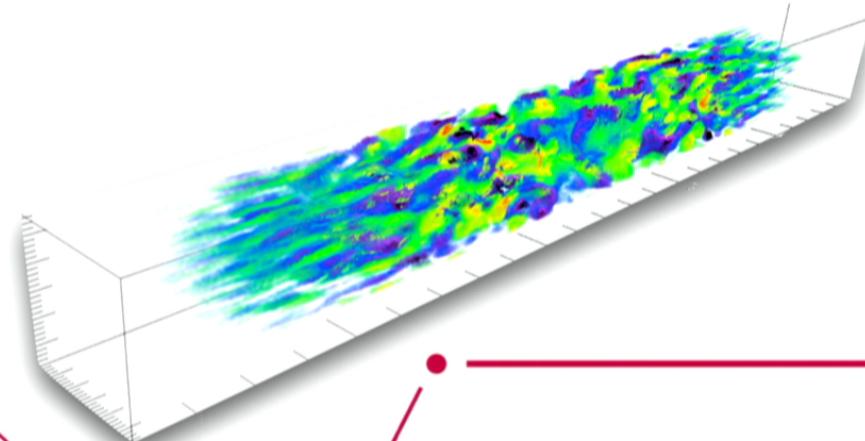
Pair-driven plasma instabilities: from astrophysics to the laboratory *in silico*

Frederico Fiúza

fiuza@slac.stanford.edu



U.S. DEPARTMENT OF
ENERGY
Office of Science



SLAC NATIONAL
ACCELERATOR
LABORATORY
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Outline

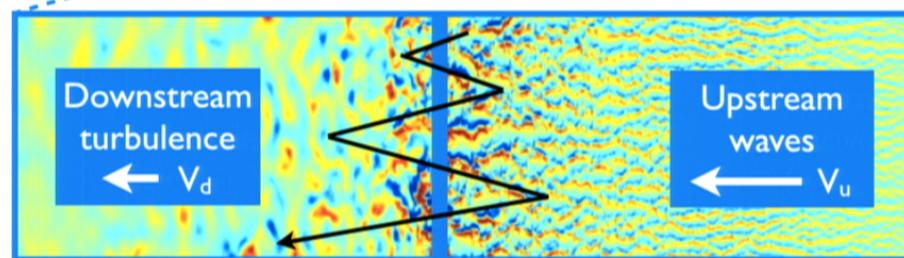
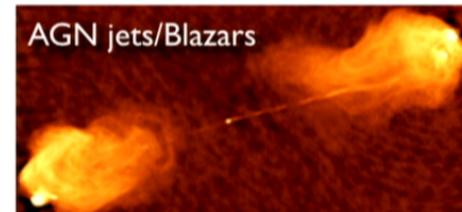
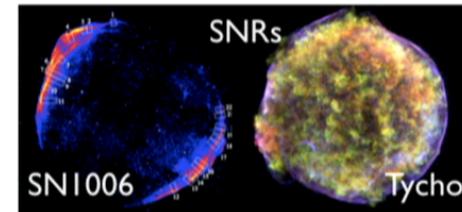
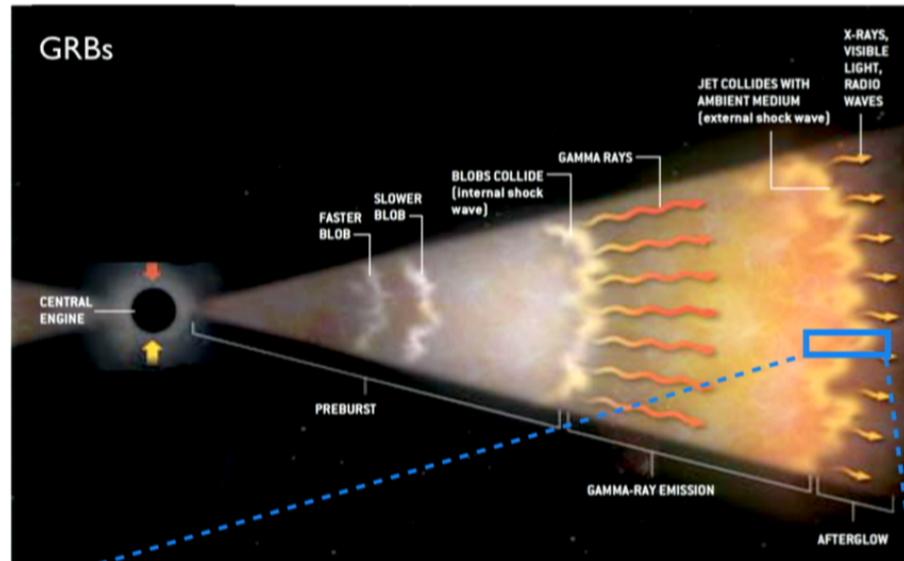


- **Introduction/Motivation**
- **Demonstration of B-field amplification by the ion Weibel/current-filamentation instability**
- **Generation of relativistic pair flows from laser-plasma interactions**
- **Simulations of pair beam-plasma instabilities**
- **Conclusions**

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Kinetic plasma processes can play an important role in astrophysics

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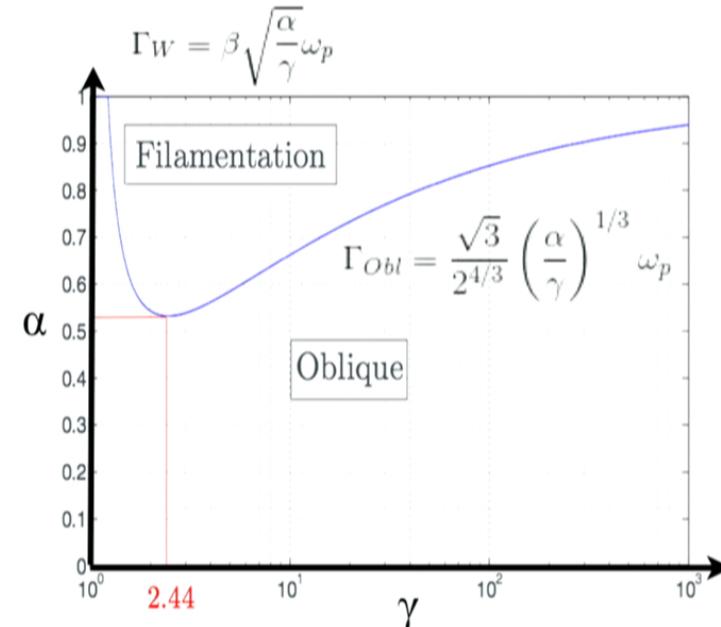
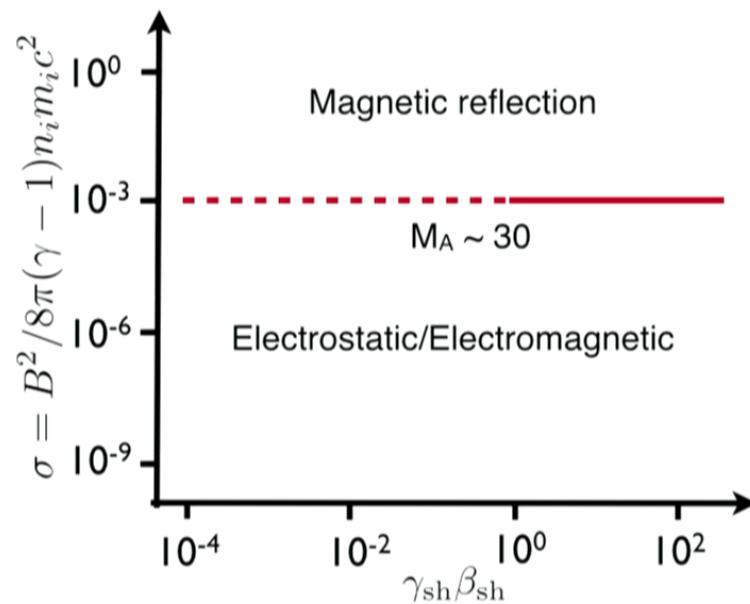
N. Gehrels, L. Piro, and P.J.T. Leonard, Scientific American (2002)
R. Blandford & D. Eichler, Physics Reports 154, 1 (1987)

Which collisionless processes (plasma instabilities) mediate the slow down of energetic flows, the formation of shocks, and the acceleration of particles?

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Beam-plasma interaction depends on the plasma conditions

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We want to understand the plasma physics that governs these different regimes

A. Bret, L. Gremillet, M. Dieckmann, Phys. Plasmas 17, 120501 (2010)

L. Sironi, A. Spitkovsky, J. Arons, ApJ 711, 22 (2013)

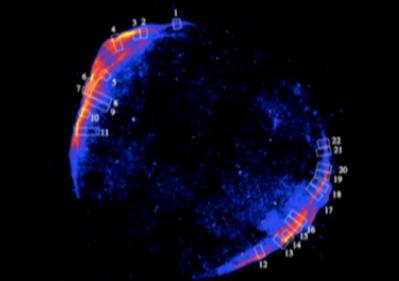
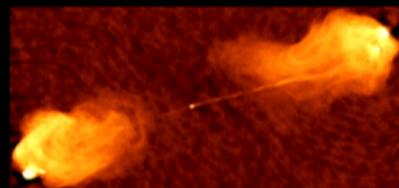
A. Stockem, F. Fiúza et al., Sci. Reports 4, 3934 (2014)

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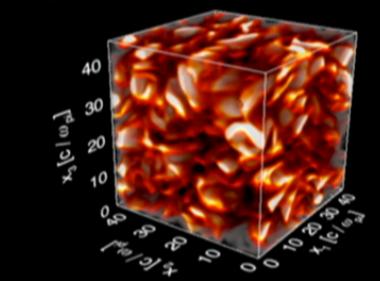
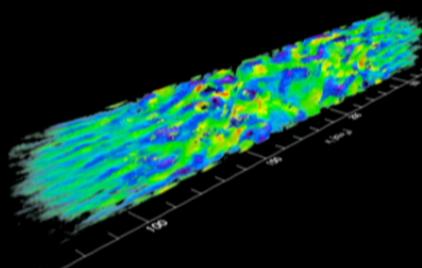
Simulations can bridge gap between astrophysical and lab plasmas

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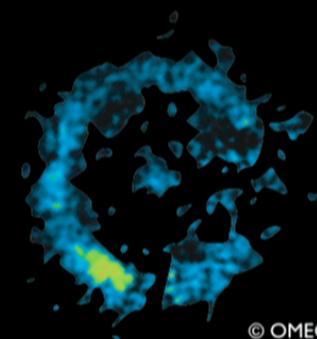
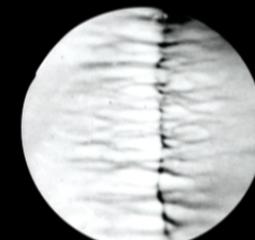
Astrophysics



Ab initio modeling



Laboratory Plasmas



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OSIRIS 3.0: modeling plasmas from first principles

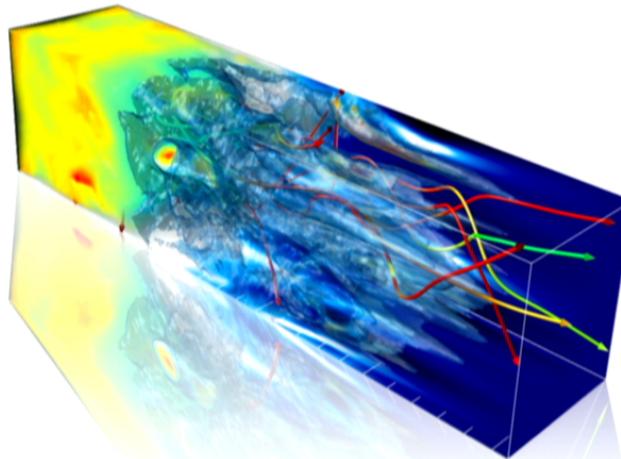
osiris
v2.0



UCLA

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
⇒ UCLA + IST



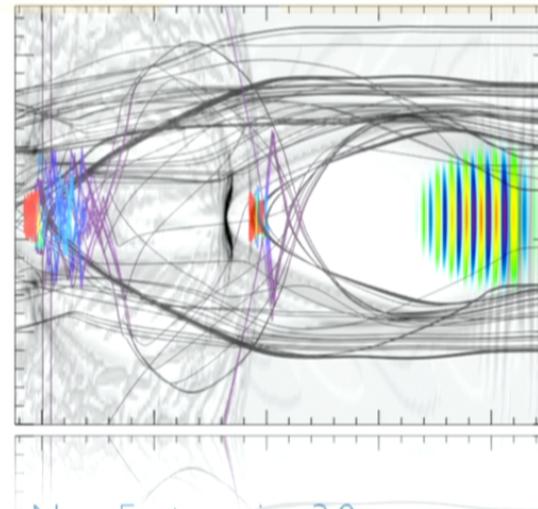
Ricardo Fonseca: ricardo.fonseca@ist.utl.pt

Frank Tsung: tsung@physics.ucla.edu

<http://cfp.ist.utl.pt/golp/epp/>

<http://exodus.physics.ucla.edu/>

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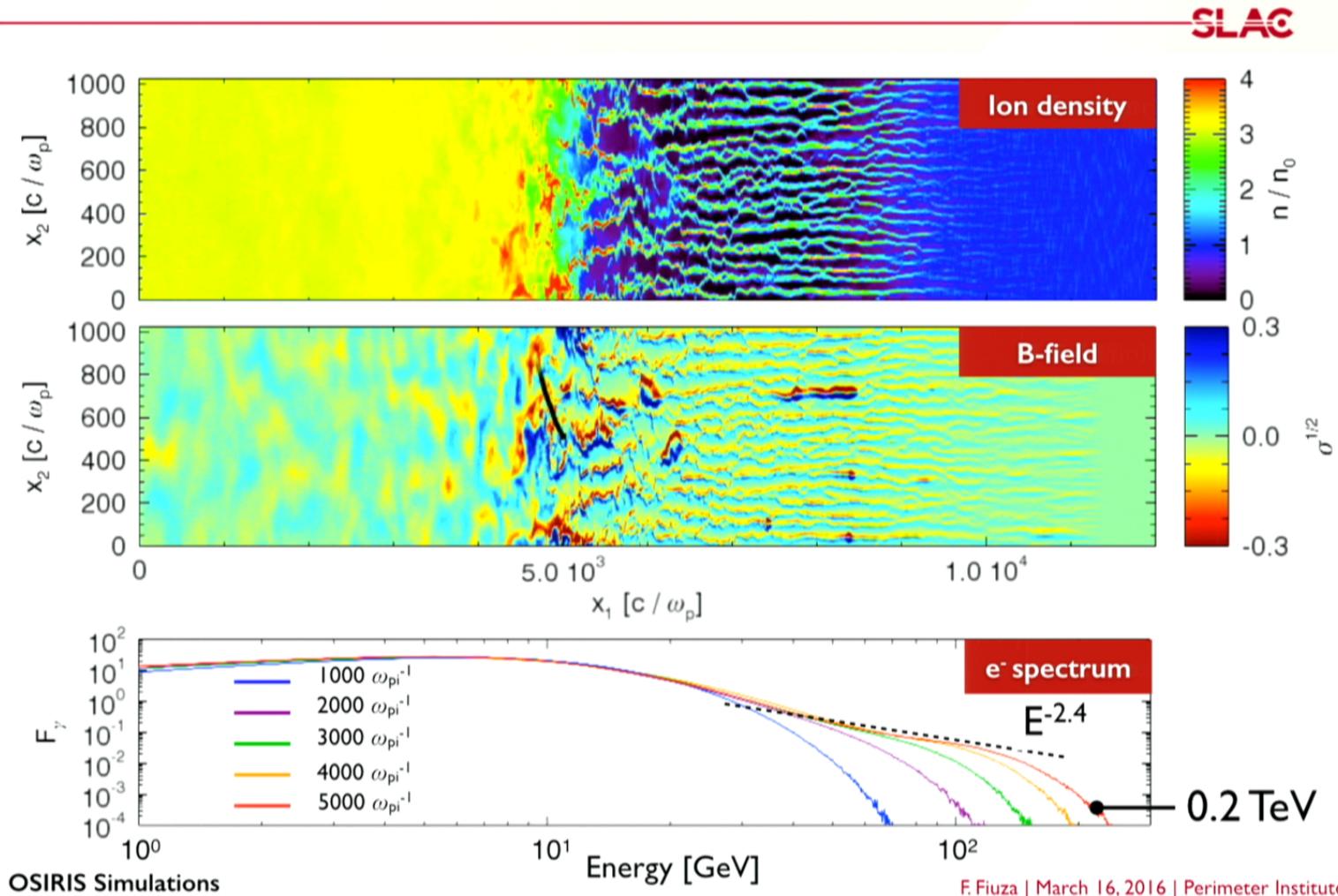
New Features in v3.0

- Parallel scalability to 1.6M cores
- High-order splines
- Boosted frame
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing

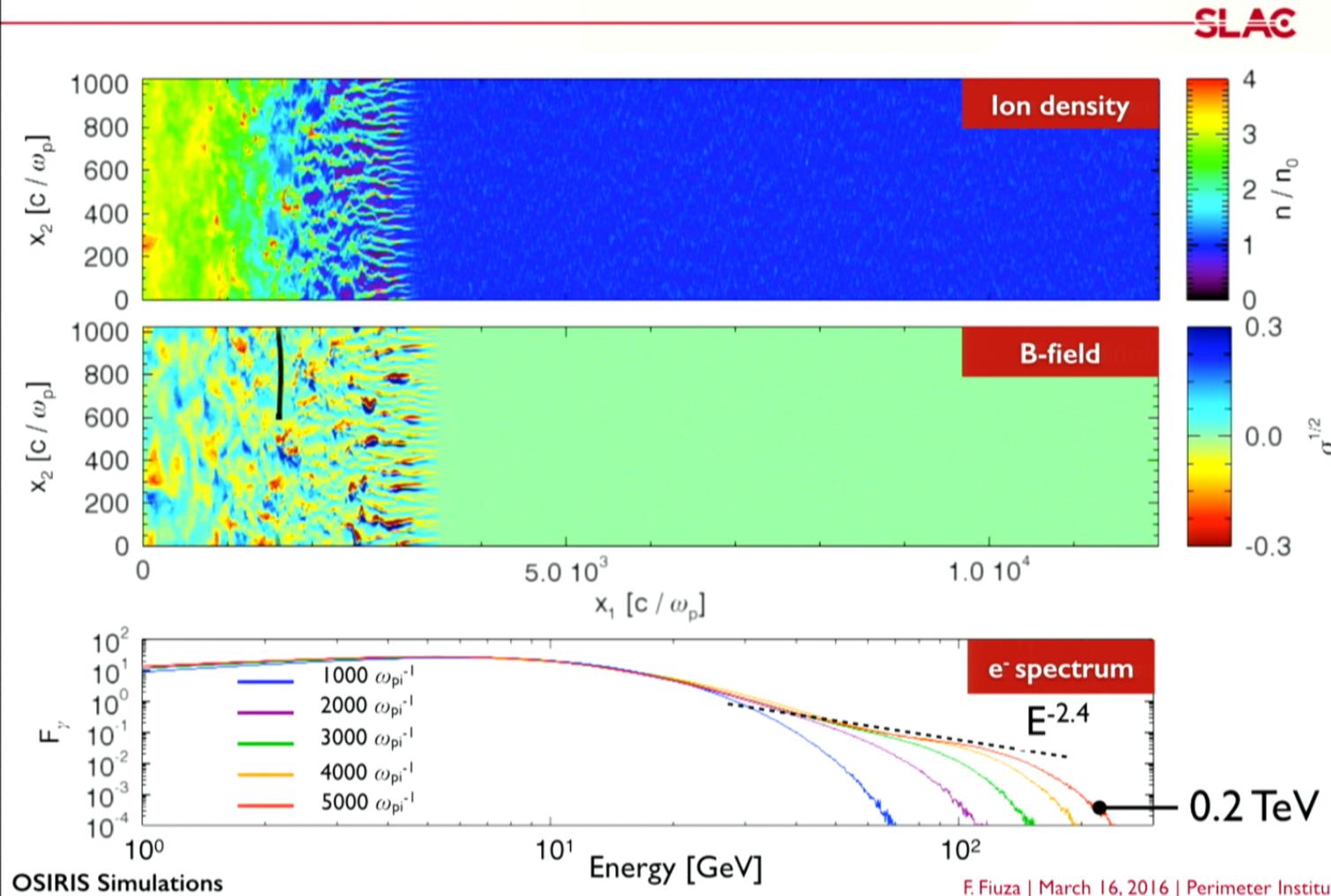


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E.g. collisionless shock formation and particle acceleration

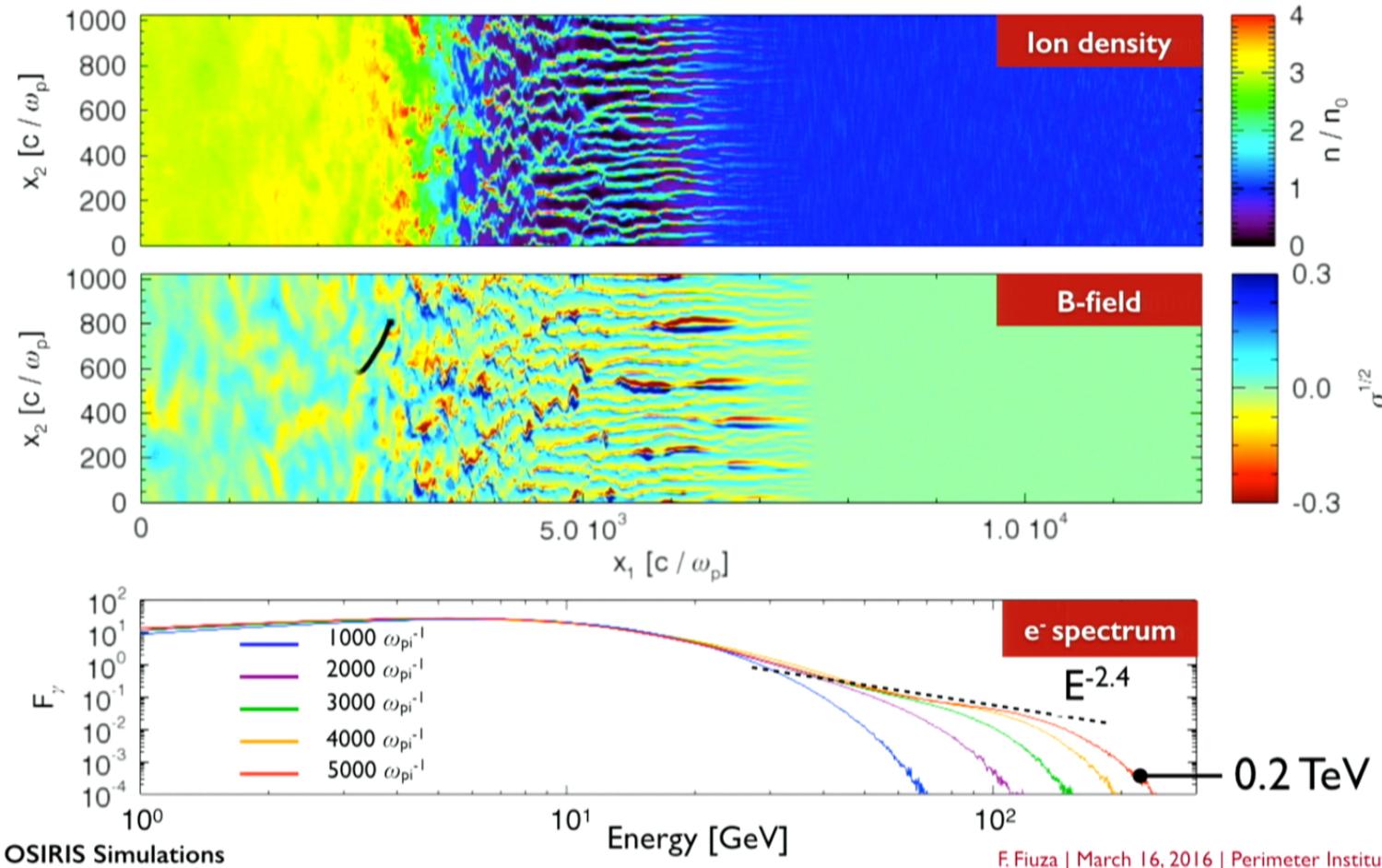


E.g. collisionless shock formation and particle acceleration



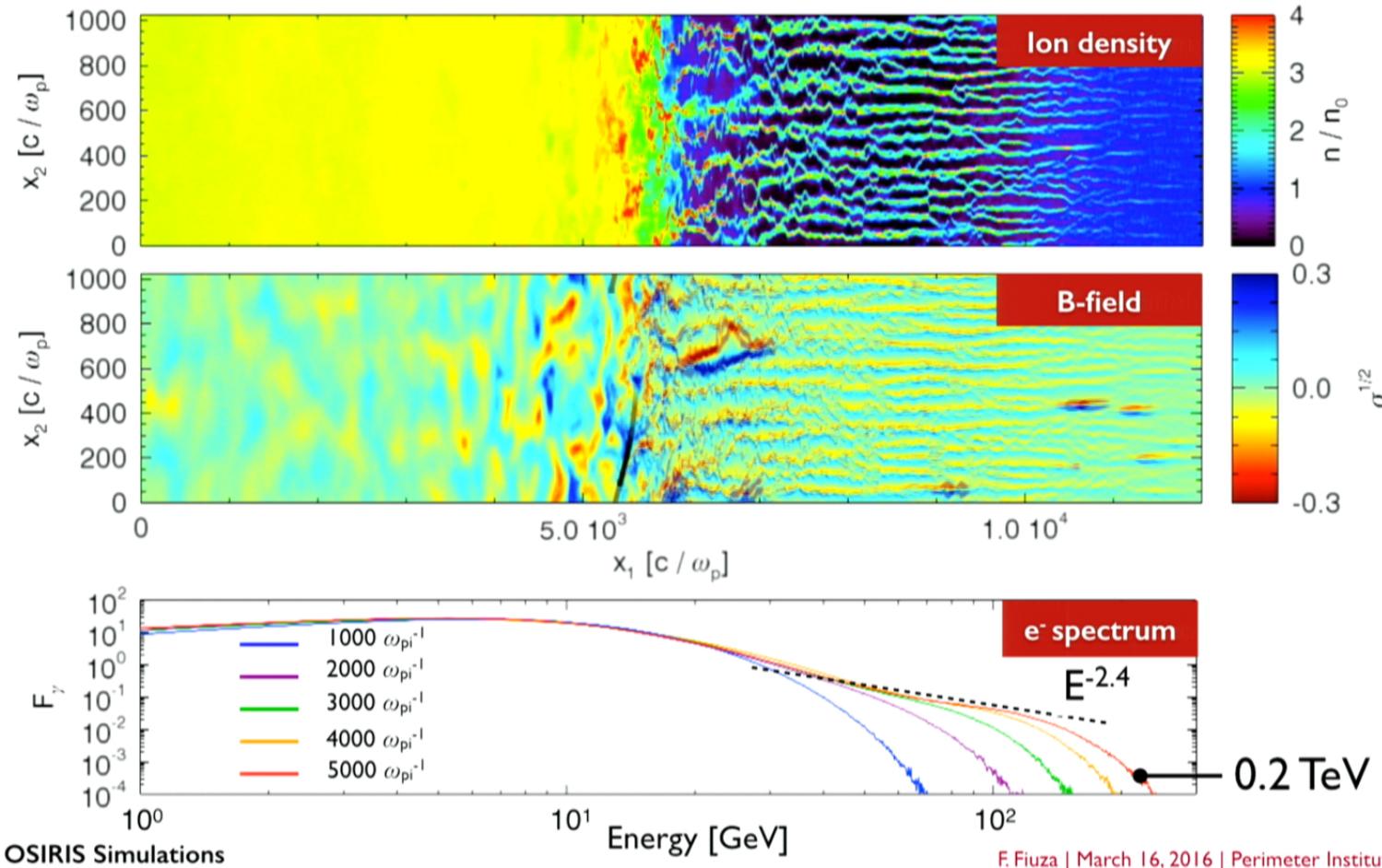
E.g. collisionless shock formation and particle acceleration

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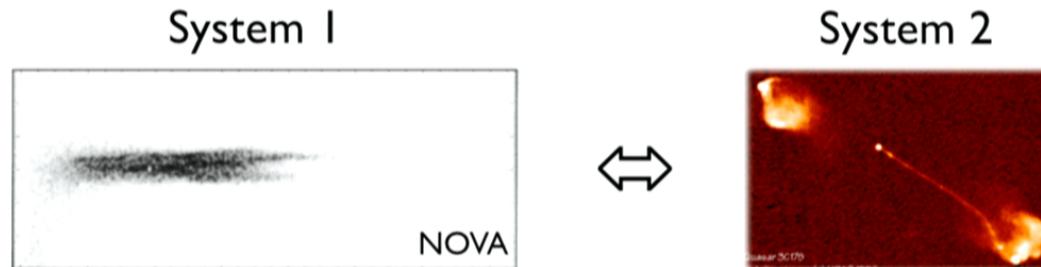
E.g. collisionless shock formation and particle acceleration

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Can we scale the plasma microphysics from astrophysics to the laboratory?

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Assumptions: collisionless systems, initially unmagnetized, with flow velocity \gg thermal velocity

The Vlasov-Maxwell equations system describing the formation of collisionless shocks depends only on 2 dimensionless parameters

$$U \equiv \frac{u}{c} \quad \mu \equiv \frac{Zm_e}{Am_p}$$

We can then scale the parameters of both systems for fixed U and μ

$$\tilde{B}_2 = \tilde{B}_1 \sqrt{\frac{n_2}{n_1}} \quad \tilde{E}_2 = \tilde{E}_1 \sqrt{\frac{n_2}{n_1}} \quad L_2 = L_1 \sqrt{\frac{n_1}{n_2}} \quad t_2 = t_1 \sqrt{\frac{n_1}{n_2}} \quad T_{i2} = \frac{A_2}{A_1} T_{i1}$$

D. D. Ryutov et al. Plasma Phys. Control. Fusion 54, 105021 (2012)

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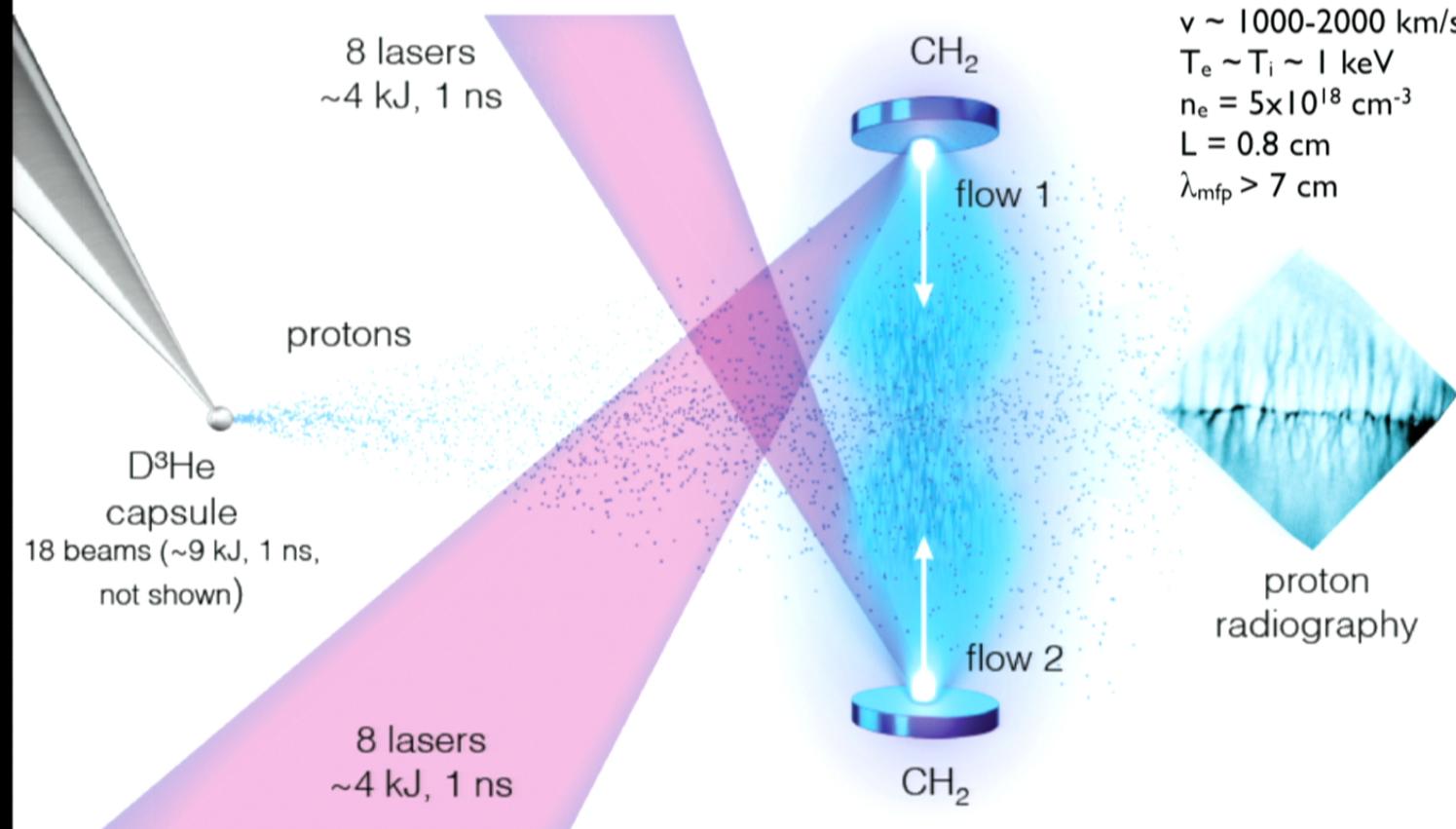
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High Mach # plasma flows can be created by laser ablation

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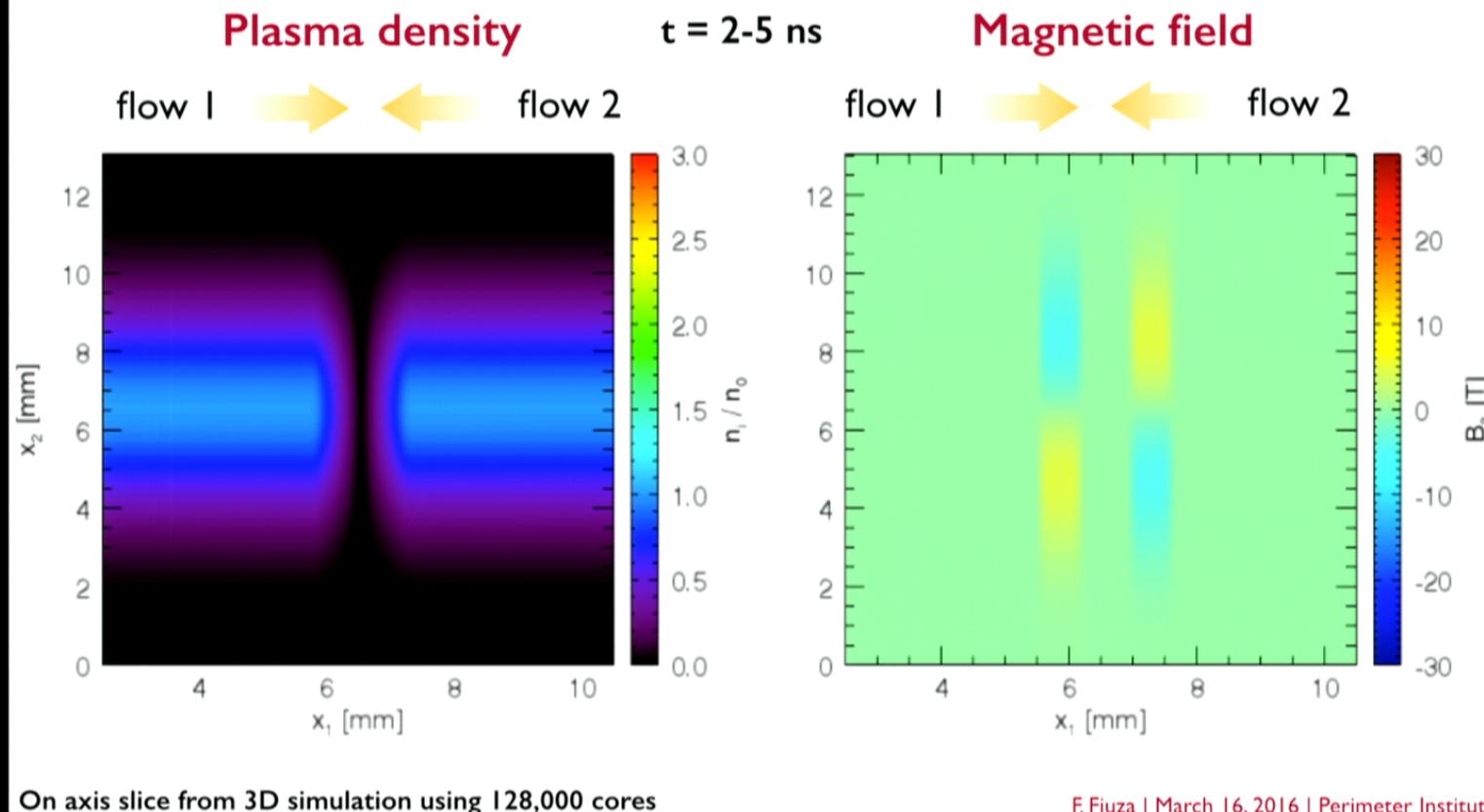
C. Huntington, F. Fiuzza et al., Nature Physics 11, 173 (2015)

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Ab initio simulations predict generation of strong Weibel B-fields

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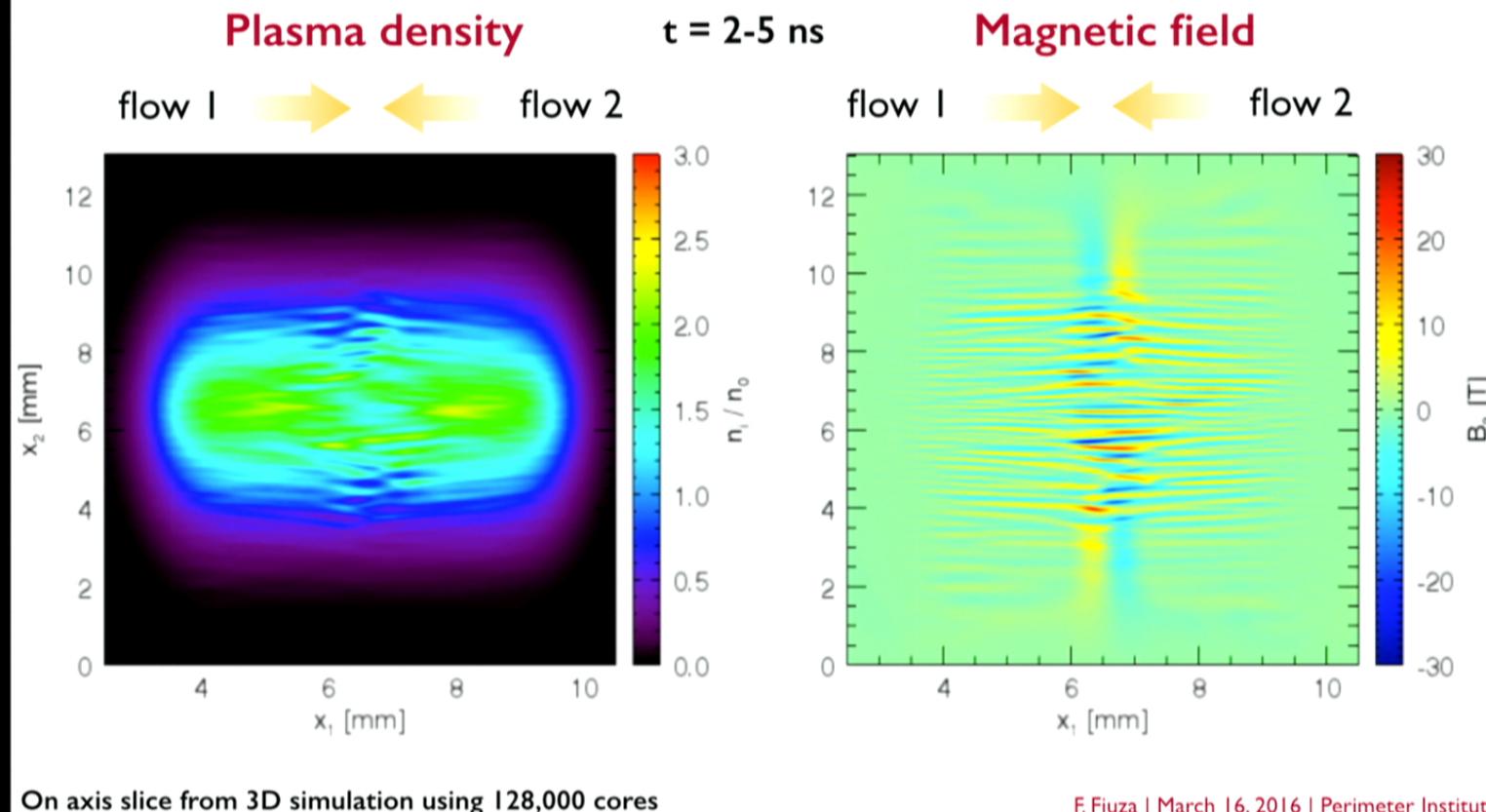
$n_e = 5 \times 10^{18} \text{ cm}^{-3}$
 $v = 1000-2000 \text{ km/s}$



Ab initio simulations predict generation of strong Weibel B-fields

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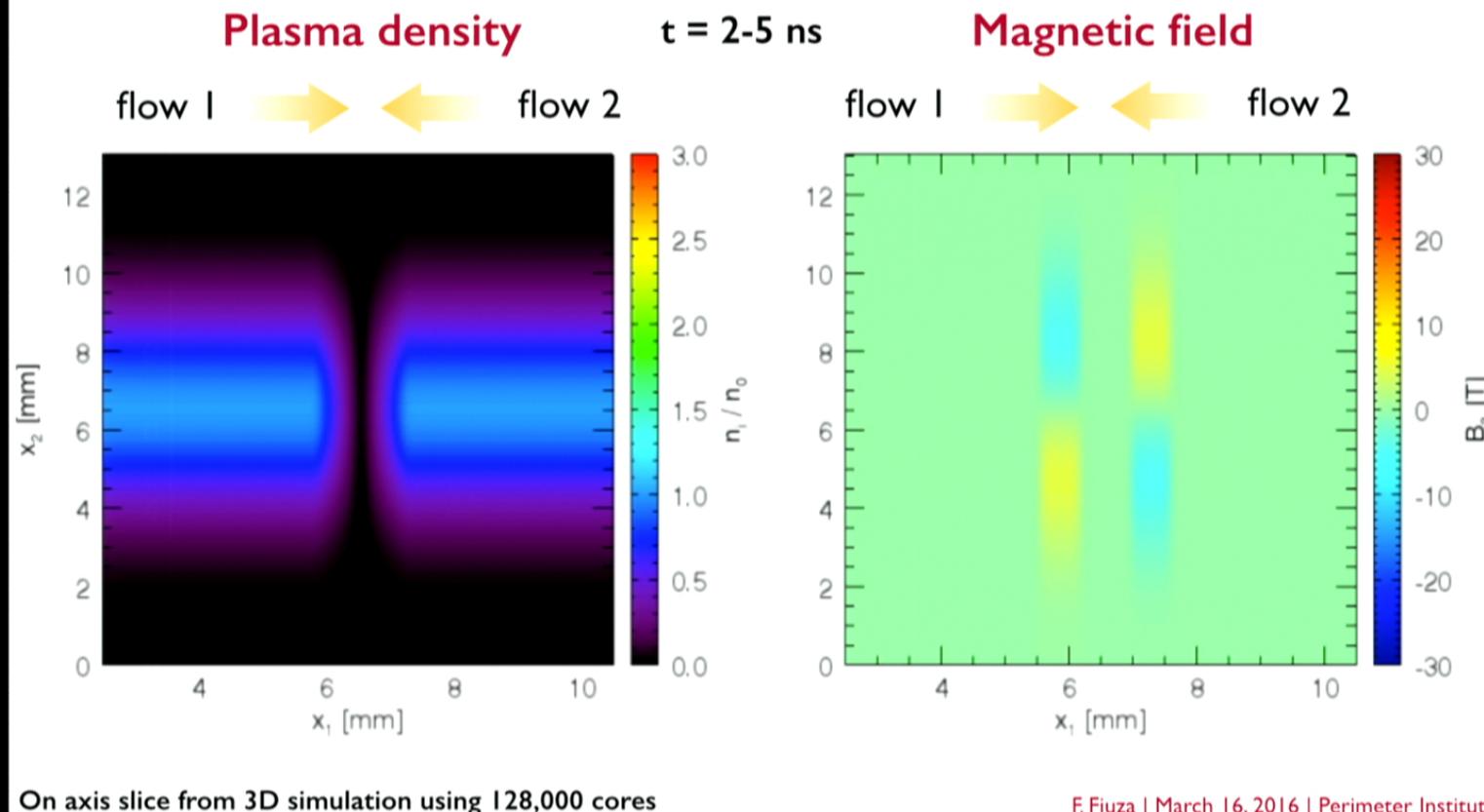
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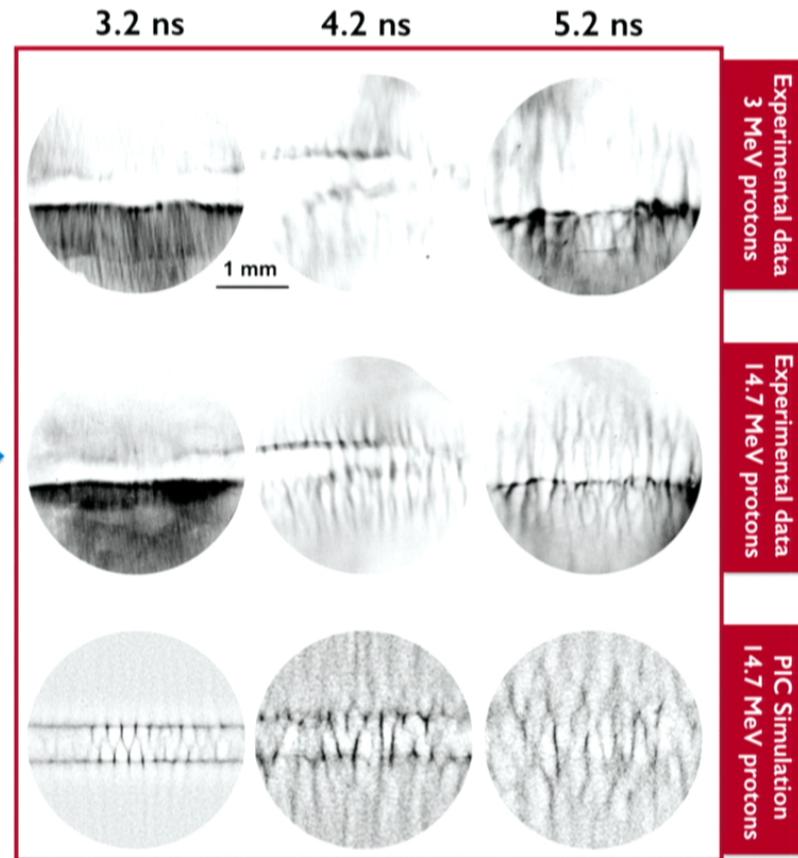
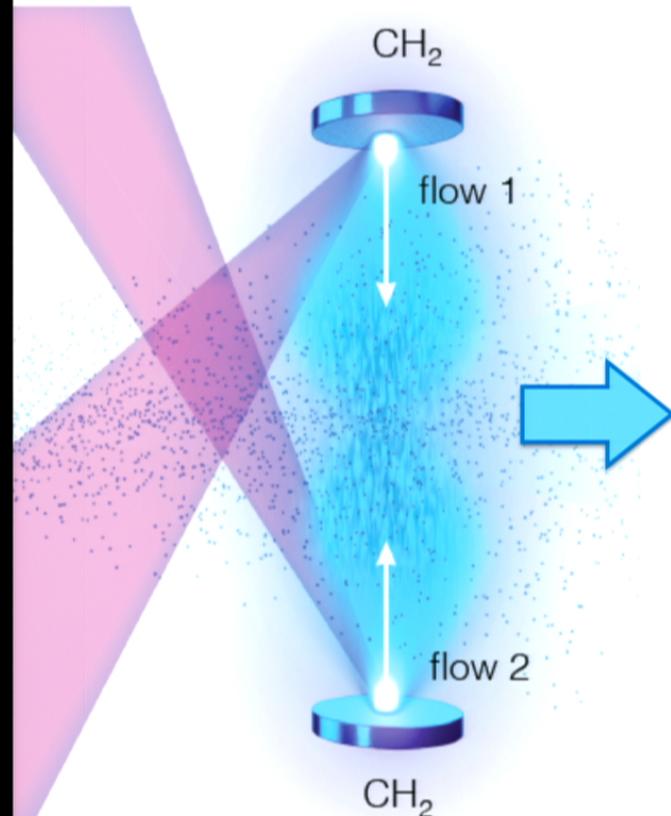
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$n_e = 5 \times 10^{18} \text{ cm}^{-3}$
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Radiography demonstrates generation of filamentary Weibel B-fields

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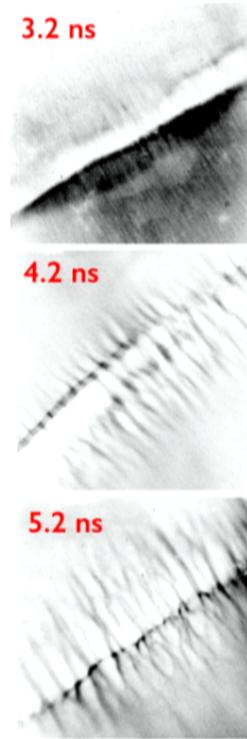
Proton deflection at 3 MeV vs. 14.7 MeV indicates magnetic fields

C. Huntington, F. Fiuzza et al., Nature Physics 11, 173 (2015)

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Our measurements show non-linear development of instability

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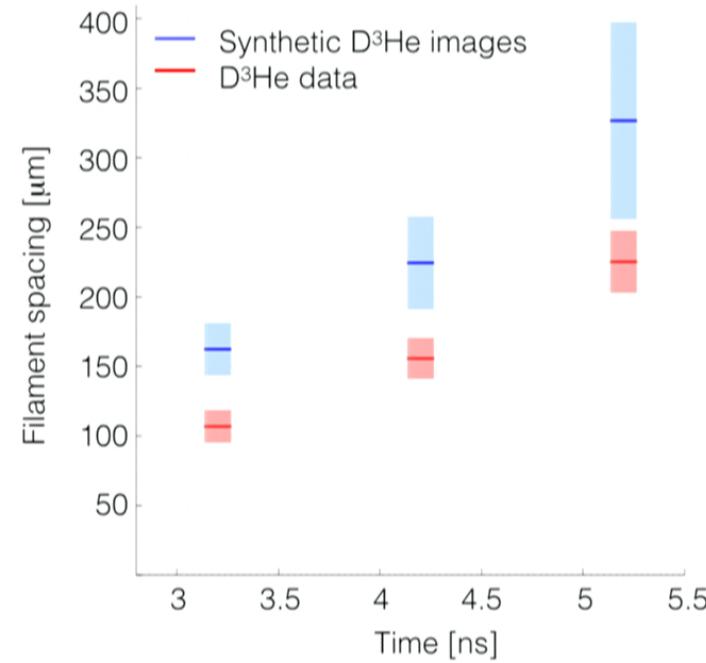


Early time interaction

Bulk flow interpenetration

Development of Weibel instability

Non-linear development of Weibel instability



Simulations and experimental measurements indicate magnetization of 1%, consistent with astrophysical shocks

Shock formation requires larger interpenetration regions/higher density flows

C. Huntington, F. Fiuzza et al., Nature Physics 11, 173 (2015)

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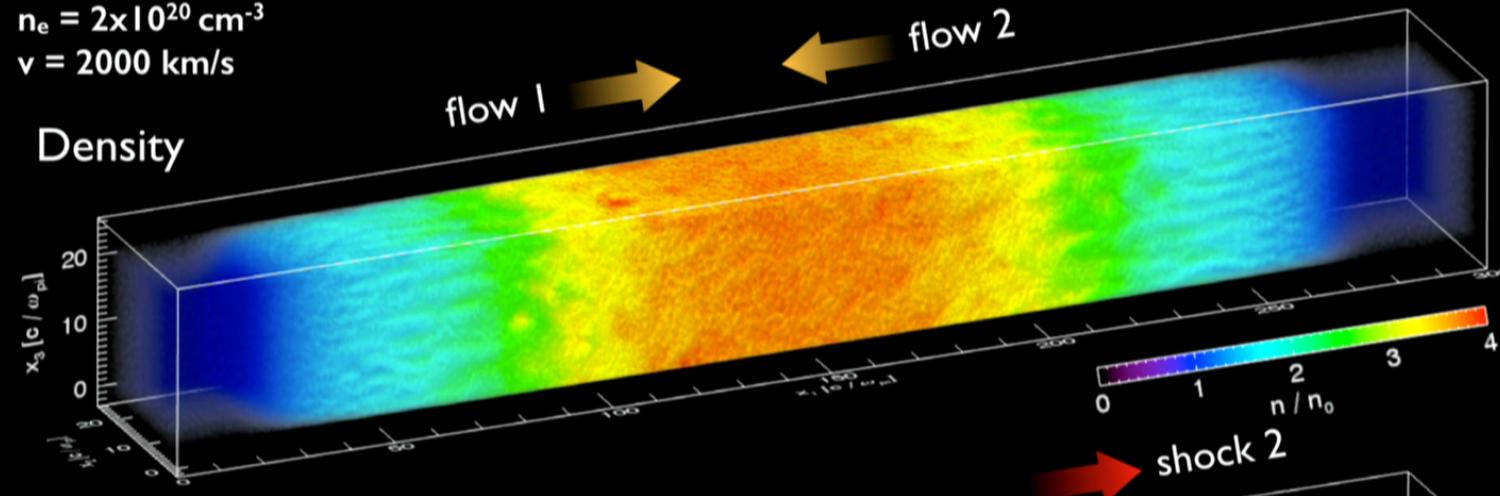
Simulations indicate possibility of shock formation for NIF conditions

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$$n_e = 2 \times 10^{20} \text{ cm}^{-3}$$

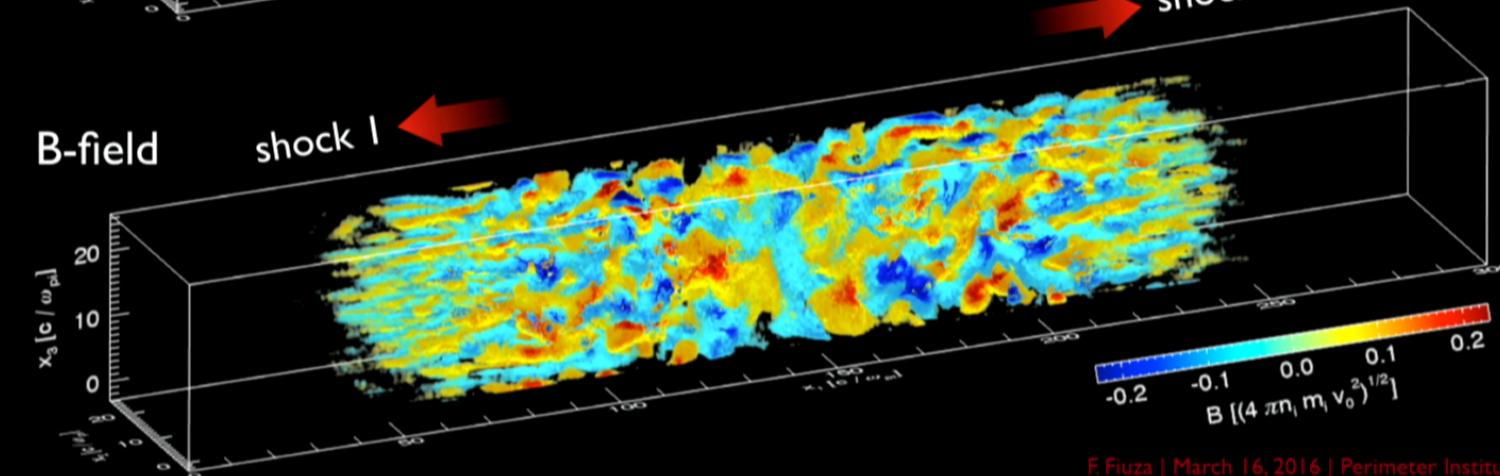
$$v = 2000 \text{ km/s}$$

Density



B-field

shock 1



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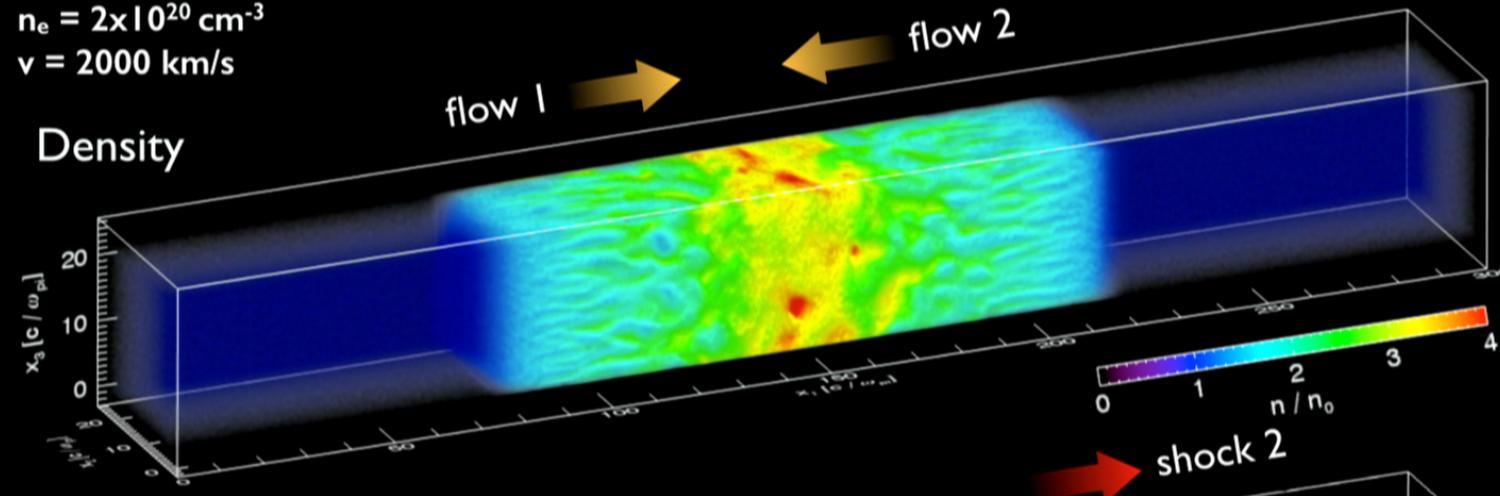
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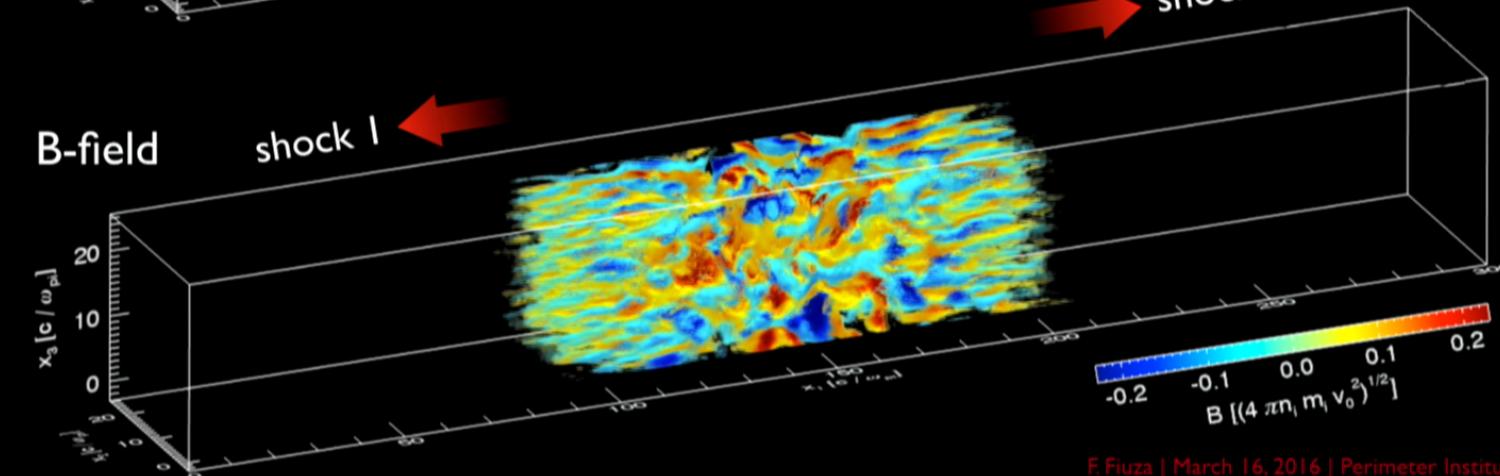
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Density



B-field

shock 1



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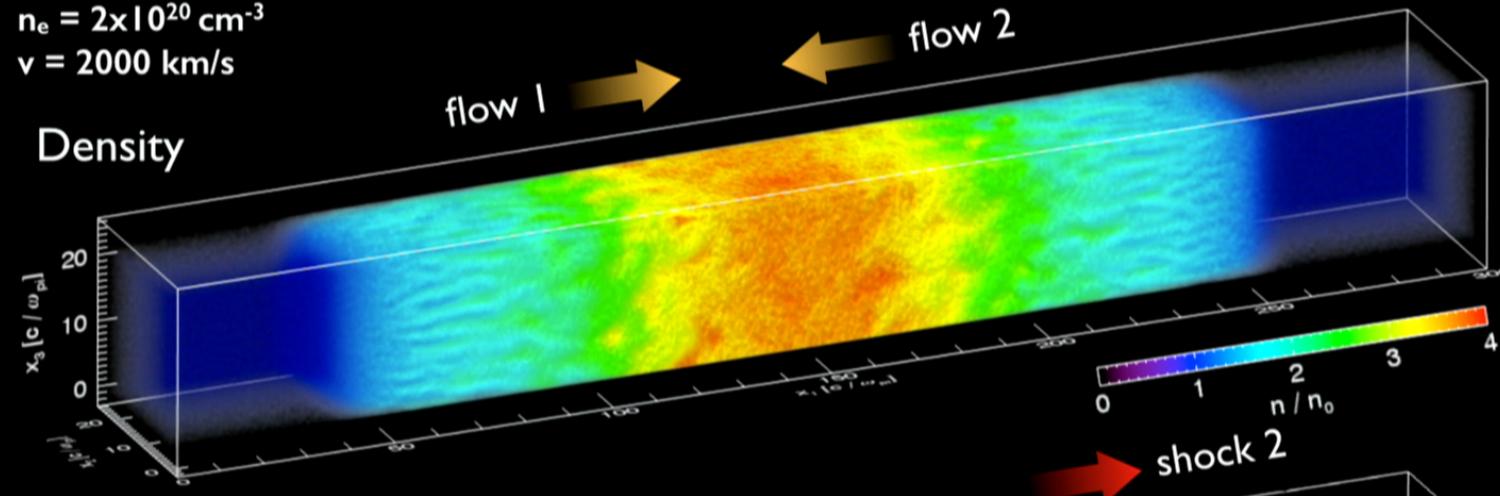
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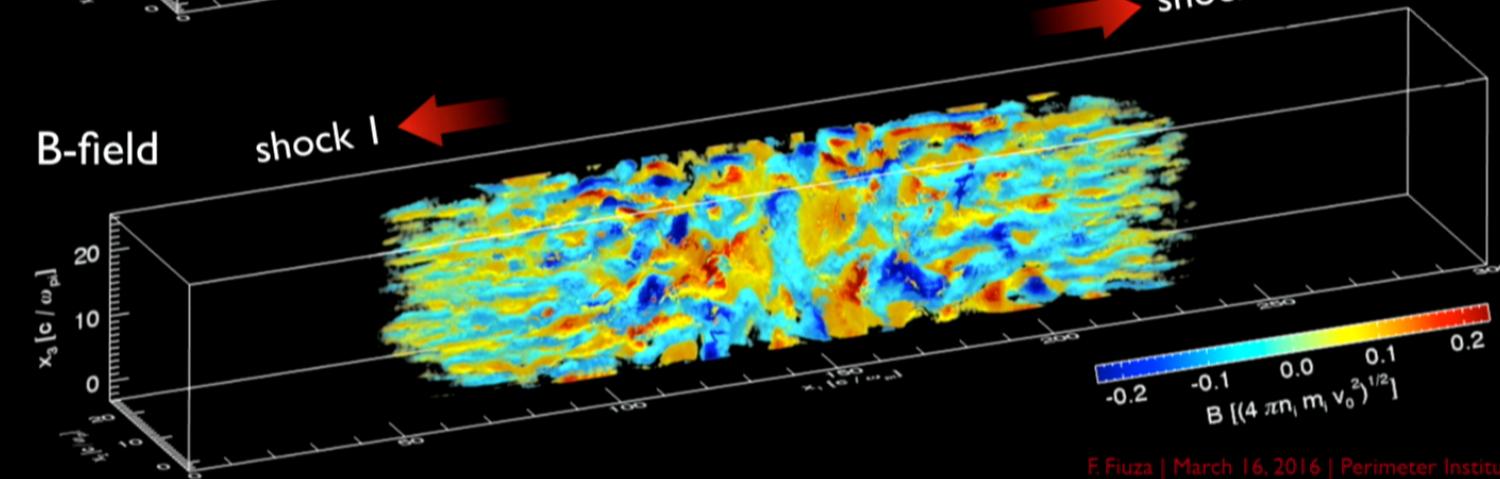
$$v = 2000 \text{ km/s}$$

Density



B-field

shock 1



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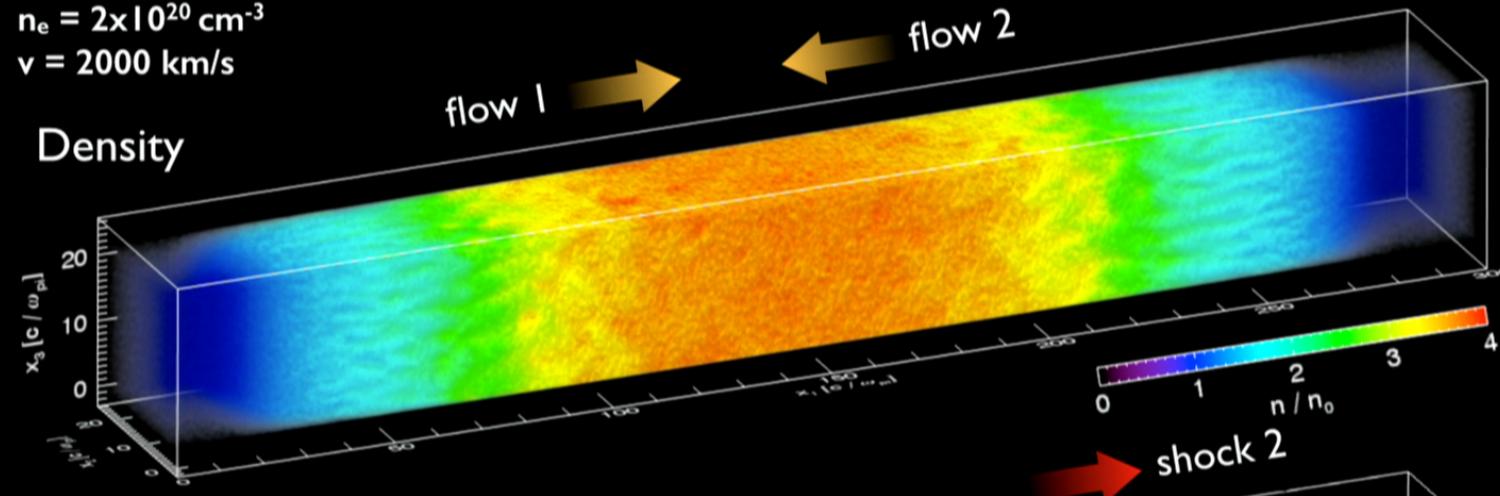
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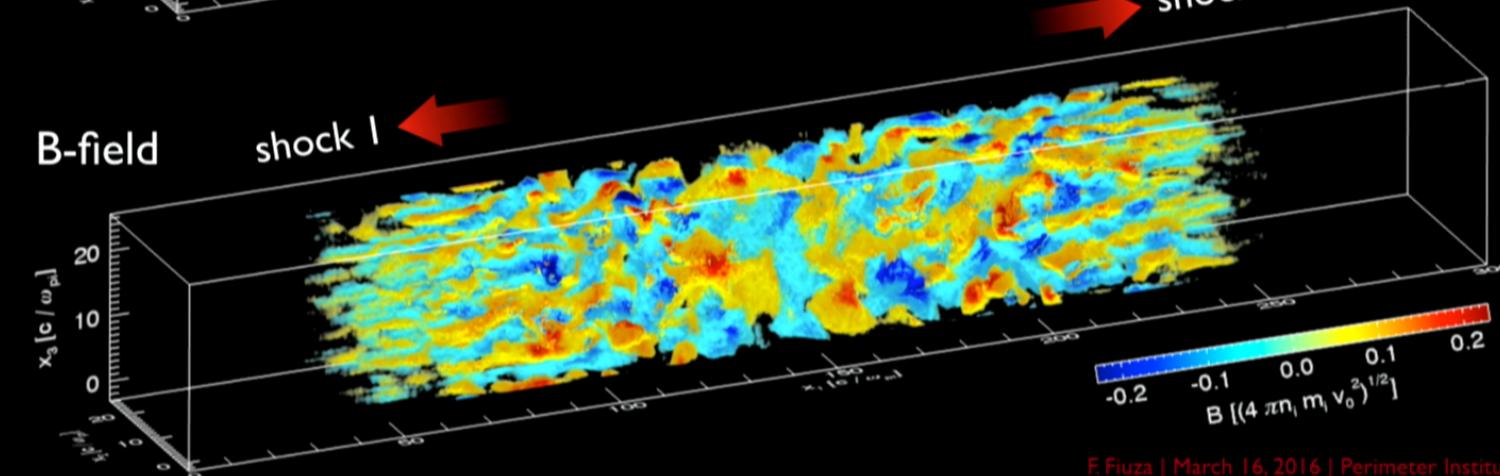
Density



shock 2

B-field

shock 1



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Outline

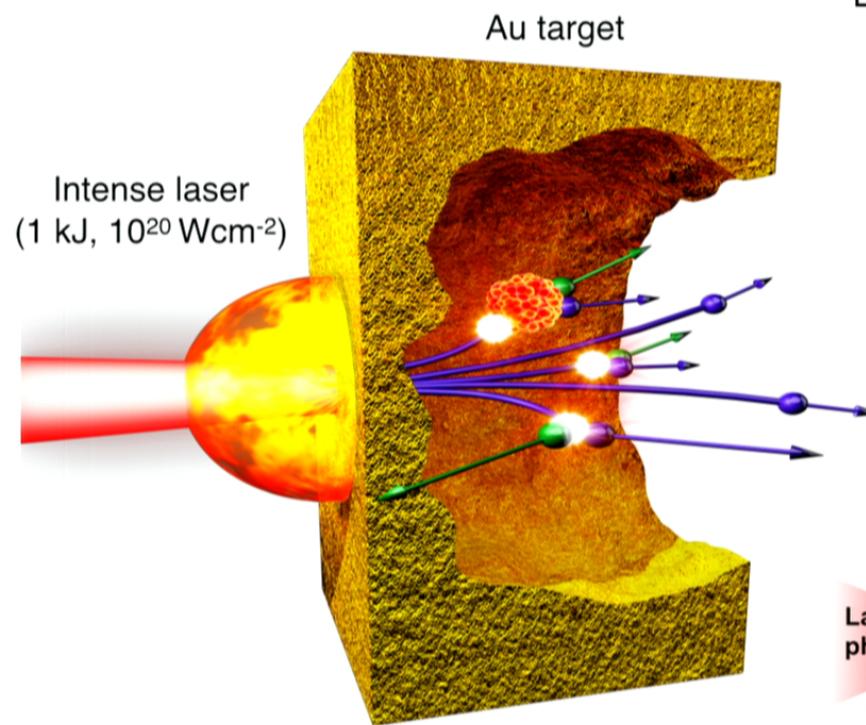
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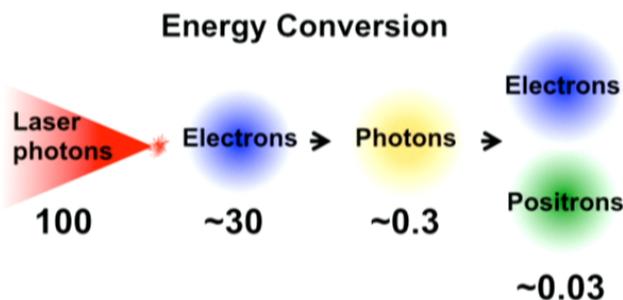
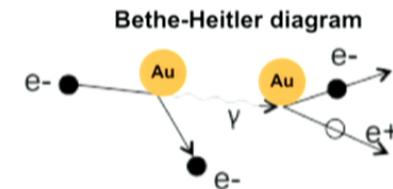
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Copious e^-e^+ pair production from intense laser-plasma interactions

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Lasers produce electron-positron pairs via the Bethe-Heitler process



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Pair production experiments were performed on four lasers

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Titan laser (LLNL)
1-10 ps, 100-350 J
5-10 shots/day



Omega EP (LLE)
1-10 ps, up to 1.3 kJ
Up to 16 shots/day



ORION (AWE)
2 SP beams
0.5-1 ps, up to 500 J



LFEX (ILE)
2-4 beams, 1 ps,
~1 kJ each beam

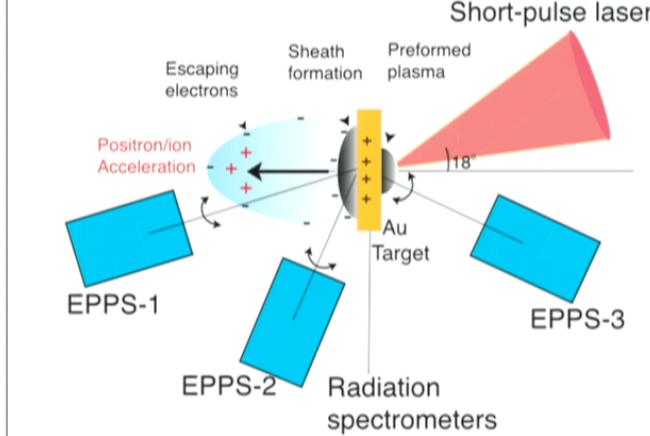
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e^- , e^+ , p^+ , and γ from Au targets were measured by various diagnostics

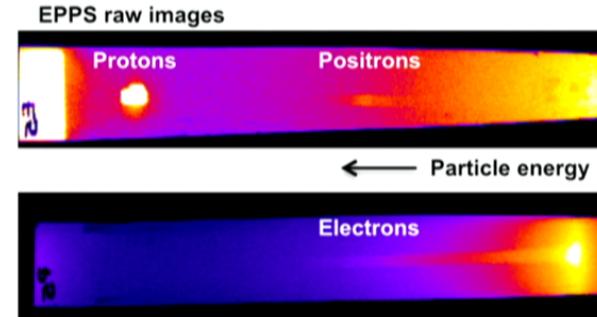
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Experiments carried by H. Chen's group (LLNL)

Experimental setup

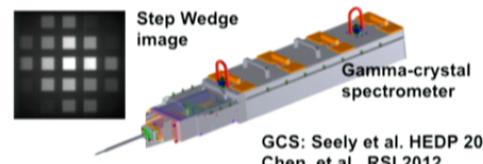


Electron, positron, proton spectrometer



EPPS: Chen, et al., RSI 2008

High-energy gamma diagnostics

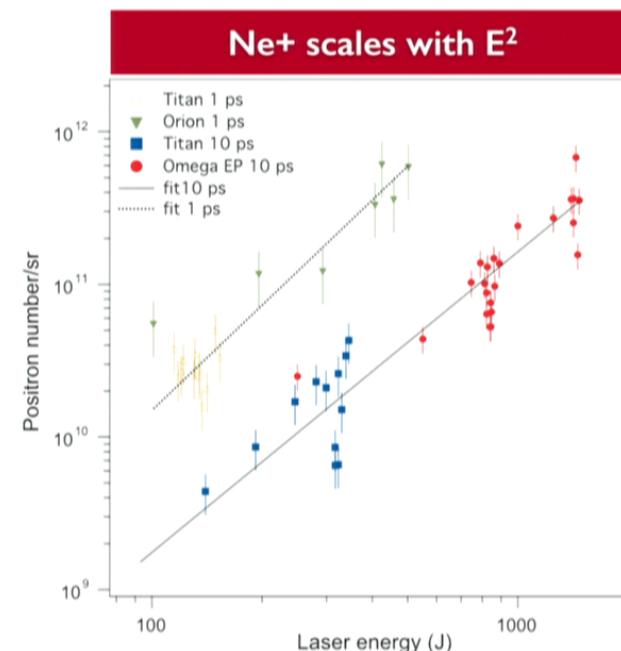
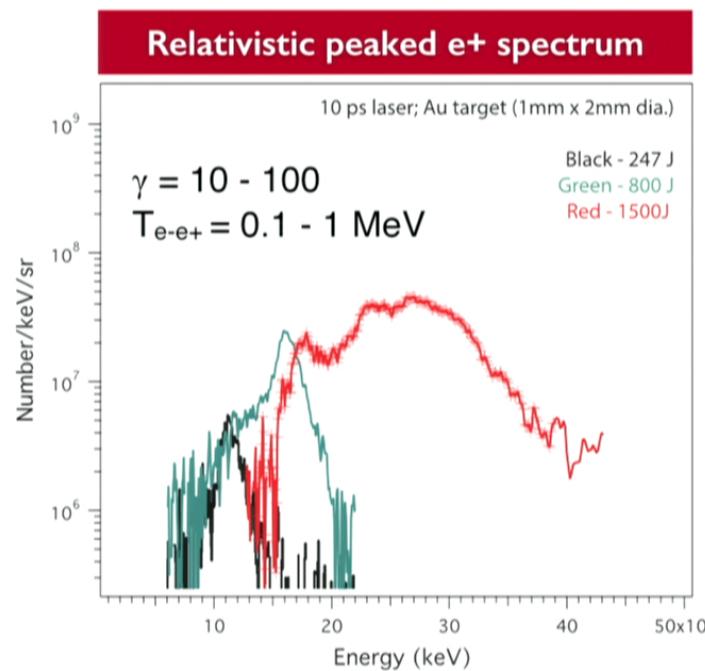


GCS: Seely et al. HEDP 2011
Chen, et al., RSI 2012

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Positron yield scales with the square of laser energy, E^2

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For current laser energy, \sim kJ, pair beam density can reach $n_b \sim 10^{14} - 10^{15}$ cm $^{-3}$

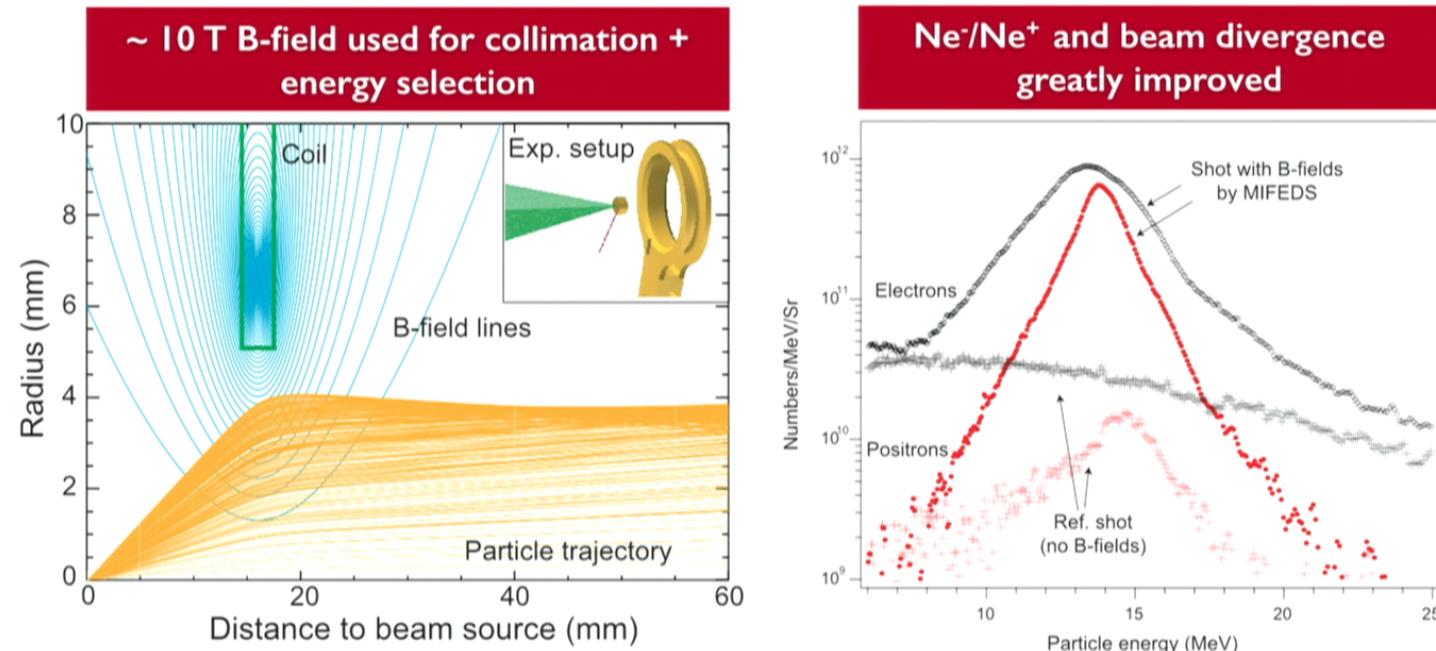
H. Chen, F. Fiuzza et al., PRL 114, 215001 (2015)

H. Chen et al., Phys. Plasmas 22, 056705 (2015)

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Demonstration of effective collimation of laser-produced pair jets

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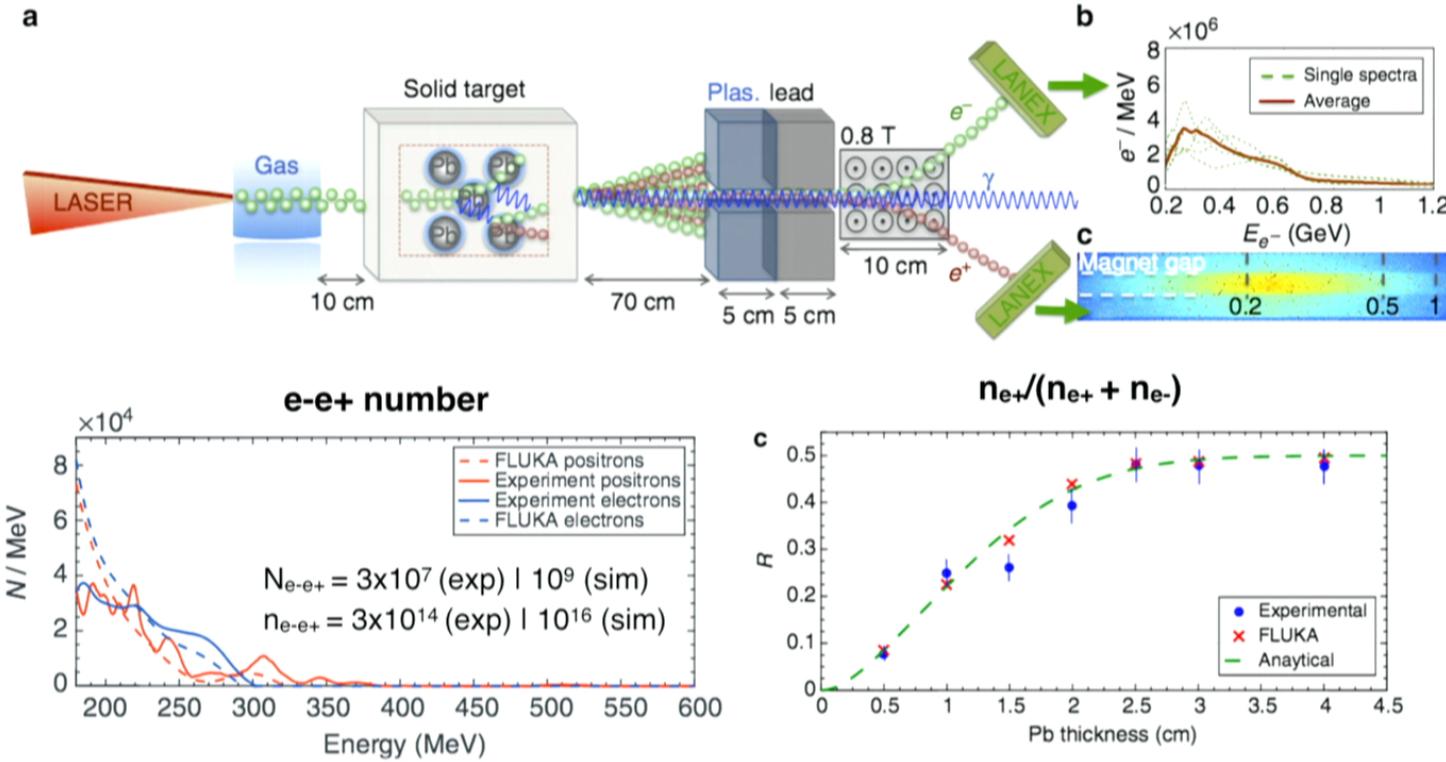
- Effective divergence of the beam reduced from 30° to 4° (FWHM)
- Effective e-/e+ ratio of the beam reduced from ~50 to 2.5

H. Chen, G. Fiksel et al., Phys. Plasmas 21, 047703 (2014)

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Pair beams can also be produced from laser-wakefield electron beam

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Charge neutrality at high energies but exponential spectrum

G. Sarri et al., Nat. Commun. 6, 6747 (2015)

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Pair jets are approaching ideal conditions for beam-plasma experiments

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Counter-streaming pair instabilities | relevant of internal shocks (e.g. GRBs)



Weibel/current filamentation instability is expected to dominate with $\Gamma_W = \sqrt{\frac{2}{\gamma}} \omega_p$

For $n_{e-e+} = 10^{15} \text{ cm}^{-3}$ and $\gamma \sim 10$ \longrightarrow • $R_{e-e+} \sim 1 \text{ mm} \sim 2 c/\omega_p'$
• $\tau_{e-e+} \sim 10 \text{ ps} \sim 8 \Gamma_W^{-1}$ \longrightarrow Linear phase

Pair beam-plasma instabilities | relevant of Blazars



Oblique instability is expected to dominate with $\Gamma_{Obl} = \frac{\sqrt{3}}{2^{4/3}} \left(\frac{\alpha}{\gamma}\right)^{1/3} \omega_p$

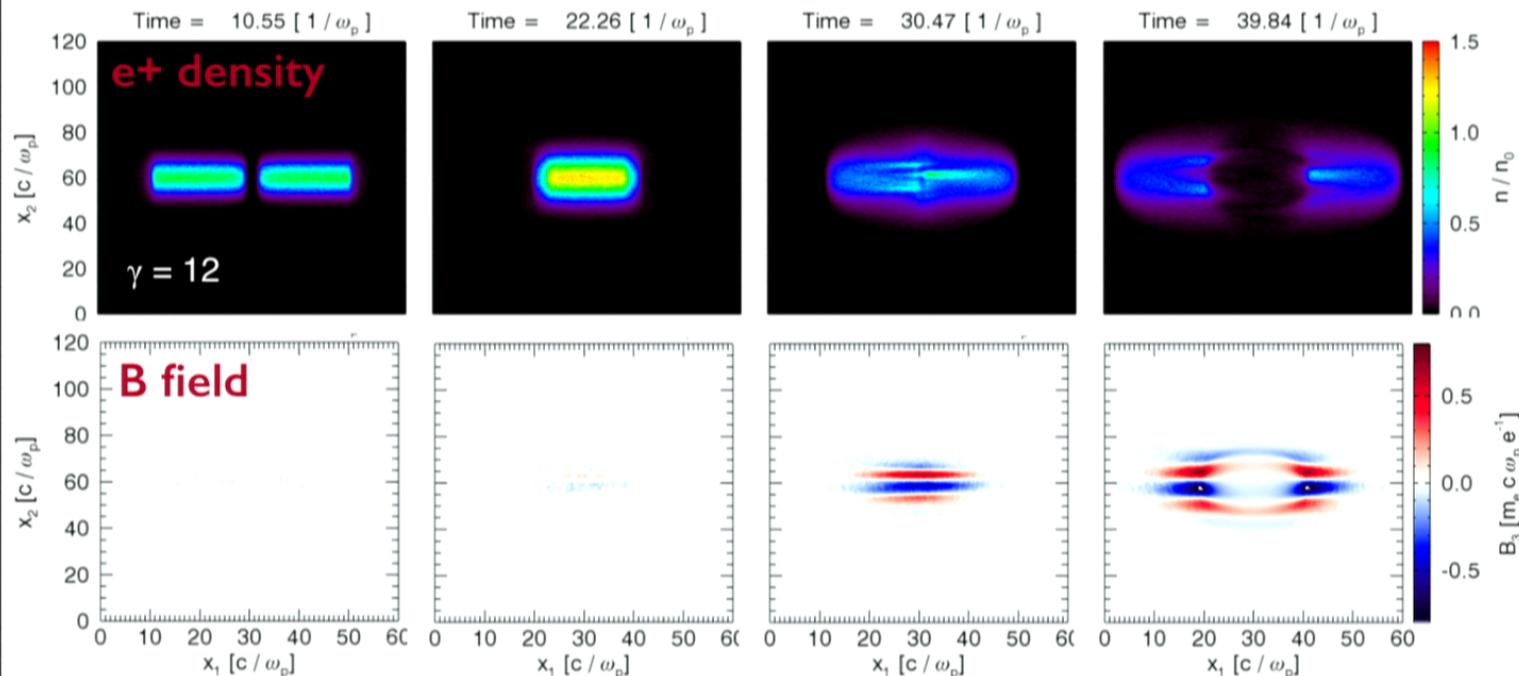
For $n_{e-e+} = 10^{15} \text{ cm}^{-3}$ and $\gamma \sim 10$ \longrightarrow • $R_{e-e+} \sim 1 \text{ mm} \sim (2/\sqrt{\alpha})c/\omega_p'$
• $\tau_{e-e+} \sim 10 \text{ ps} \sim 6\alpha^{-1/2}\omega_p'^{-1}$ \longrightarrow Linear +
• $L/c \sim 1 \text{ cm/c} \sim 20\alpha^{-1/6}\Gamma_{Obl}^{-1}$ Non-linear
phase?

It is important to improve charge density ratio to $n_e/n_{e+} \sim 1$

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Weibel-instability develops in counter-streaming pair beams

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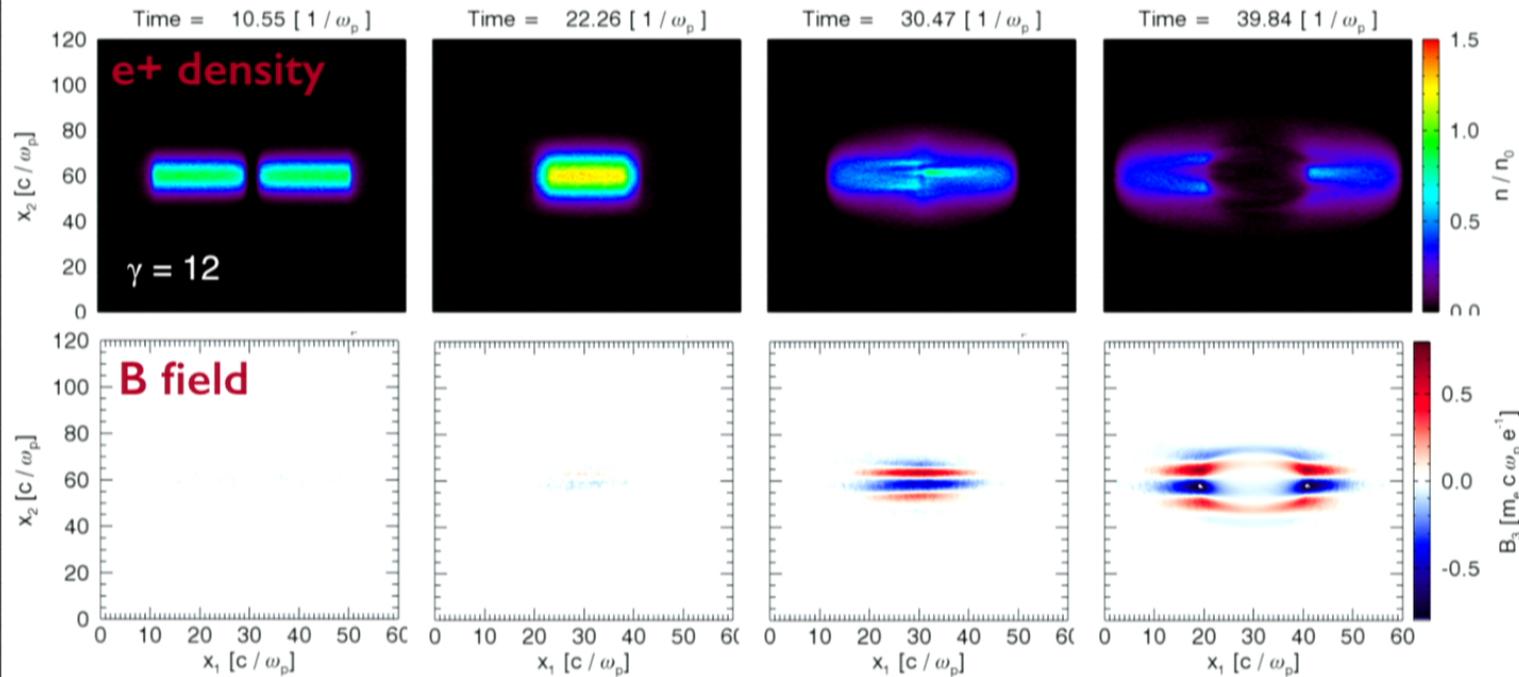
mm scale, 10 T B-fields can be probed with proton radiography

H. Chen, F. Fiuza et al., PRL 114, 215001 (2015)

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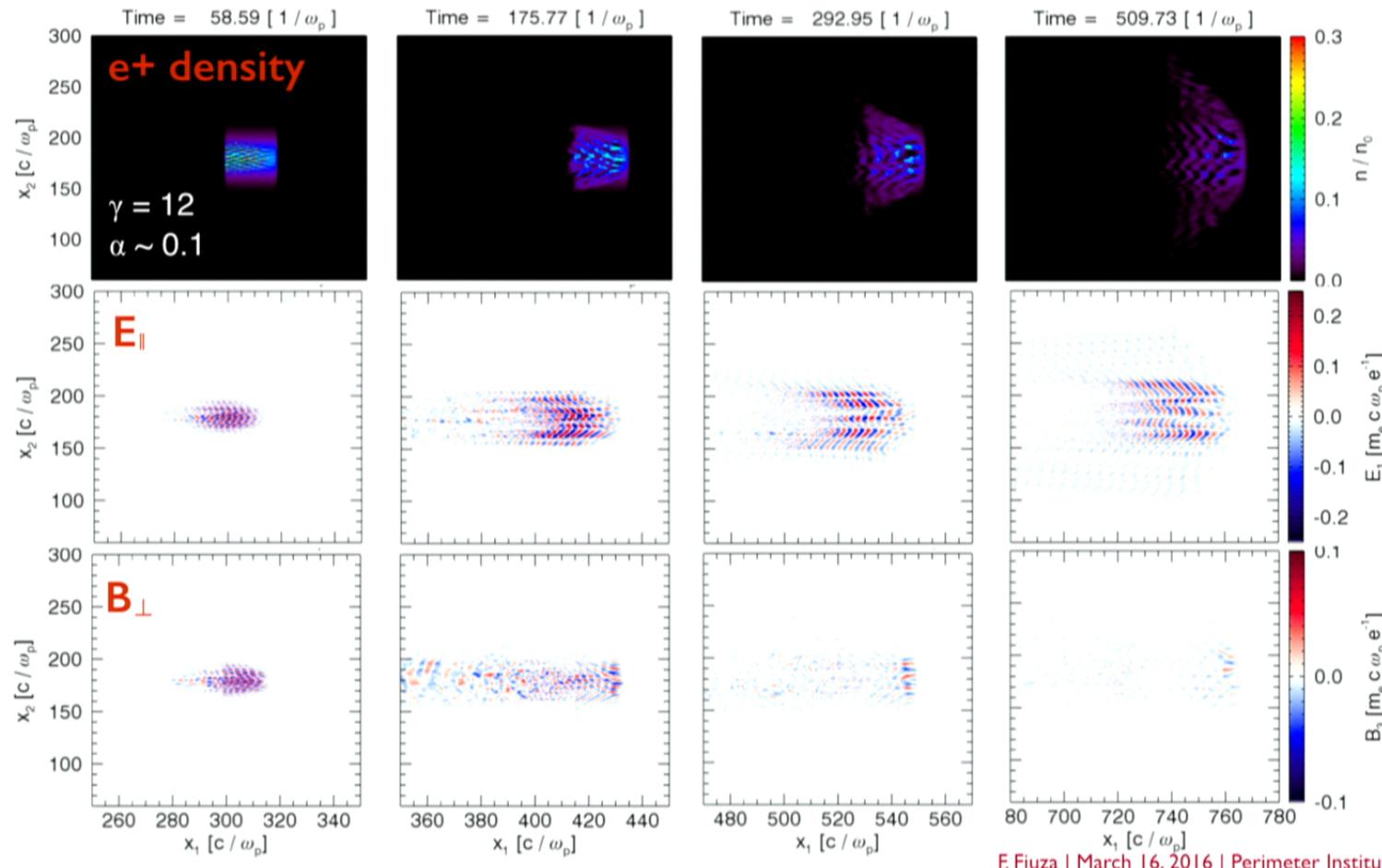
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Relativistic oblique instability can also be studied

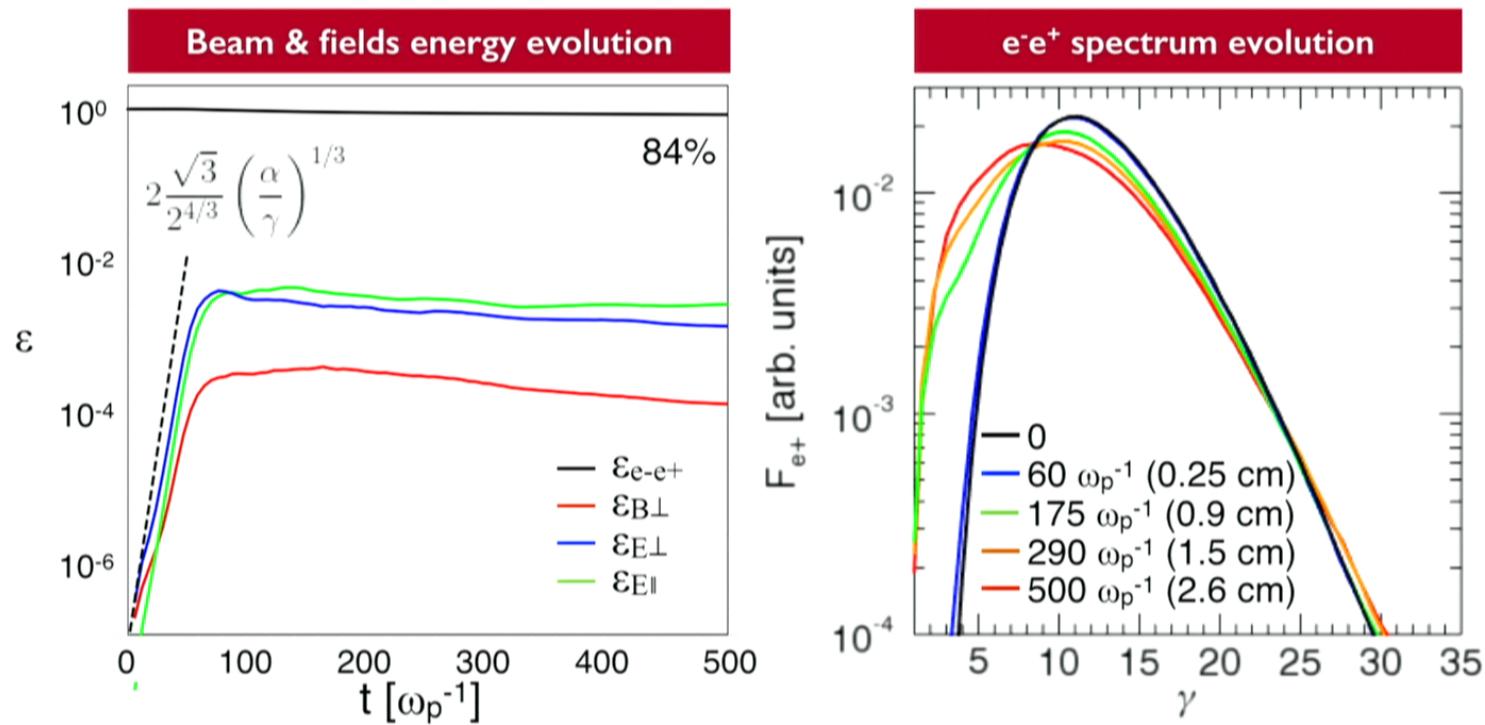
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Growth rate and beam slow-down could be measured experimentally

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$\alpha = 0.1$



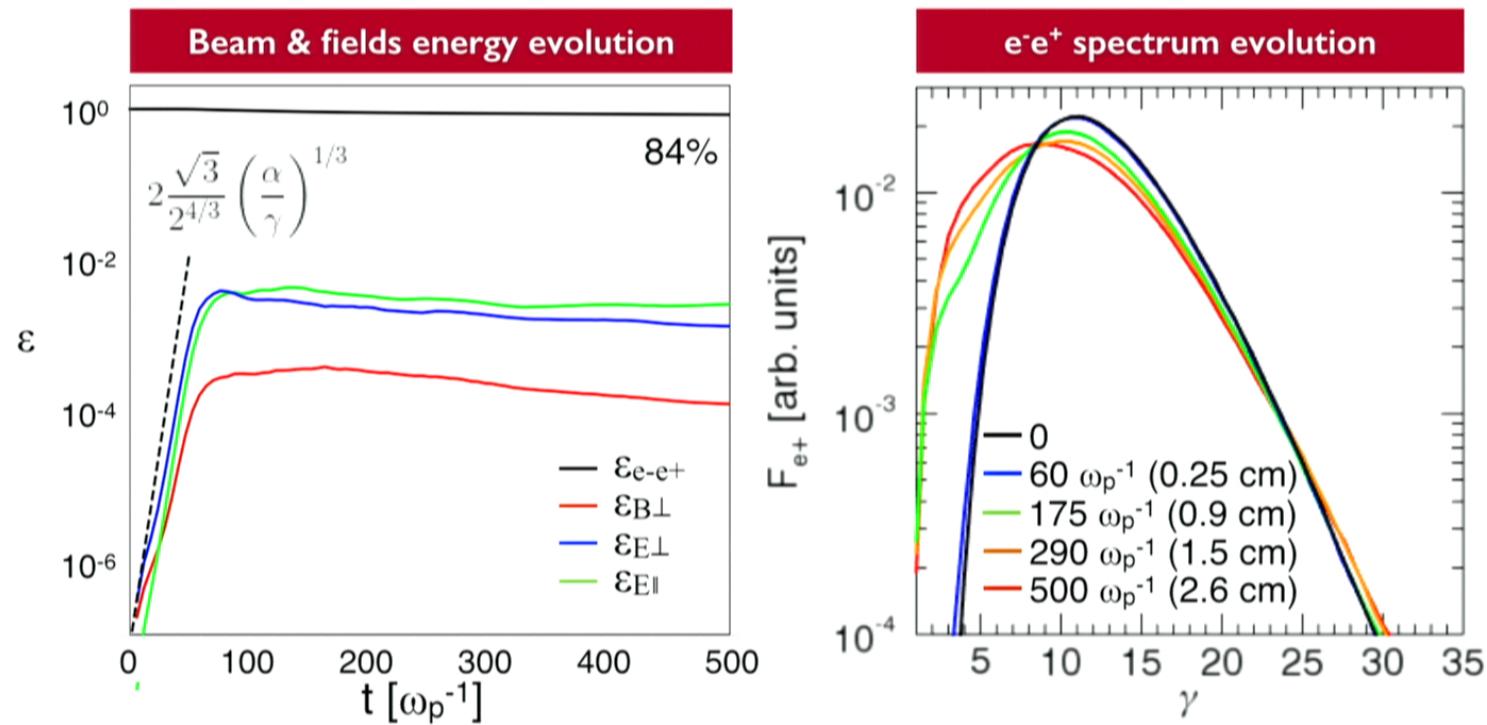
Proton radiography and spectrometers can measure field structure and e⁻e⁺ spectrum change

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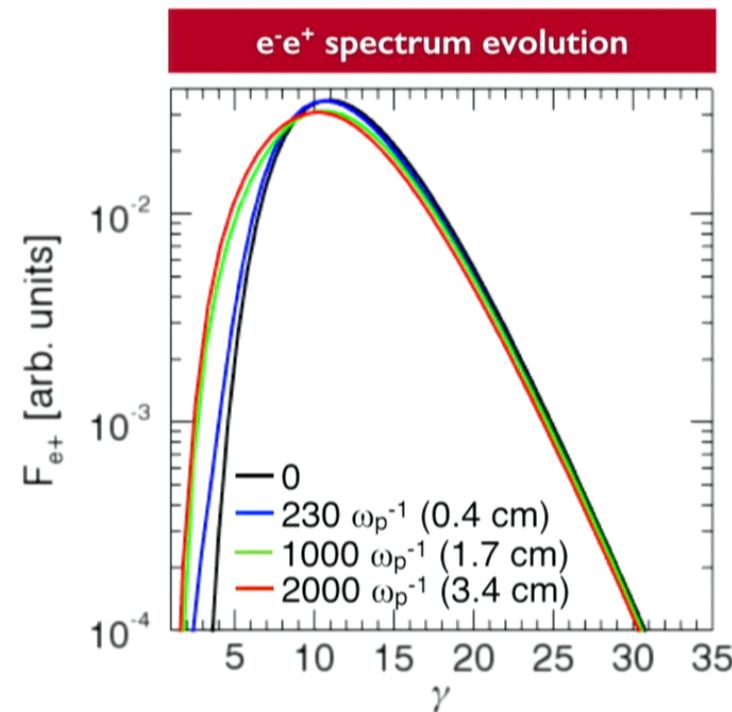
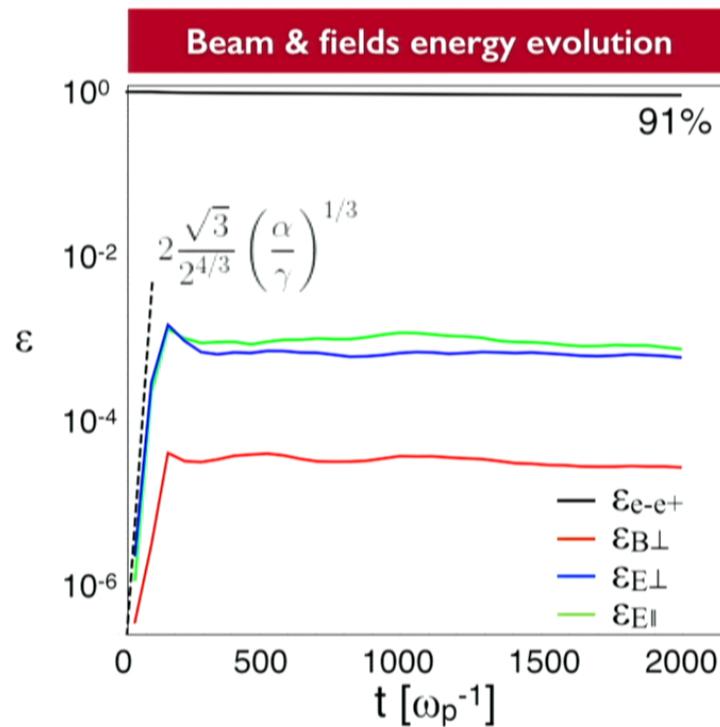
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Growth rate and beam slow-down could be measured experimentally

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$\alpha = 0.01$



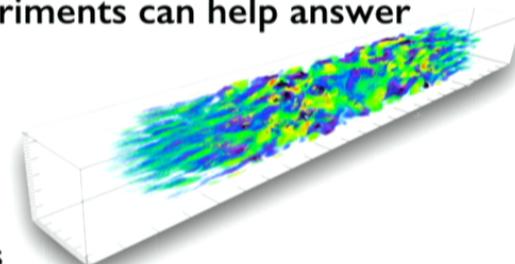
Proton radiography and spectrometers can measure field structure and e⁻e⁺ spectrum change

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Conclusions

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- Collisionless plasmas provide rich physics environments where kinetic effects play important role
- High-energy-density laser-driven plasmas offer a unique tool to probe the physics of counter-streaming collisionless plasmas
- We have demonstrated generation of ion Weibel/current-filamentation instability and generation of 1% magnetization
- We are successfully developing an experimental and modeling platform to study the physics of collisionless shocks and relativistic pair plasmas in the laboratory
- Combination of first-principles simulations and experiments can help answer critical open questions:
 - Non-linear development of plasma instabilities
 - Structure of collisionless shocks
 - Onset of turbulence and Fermi acceleration in shocks

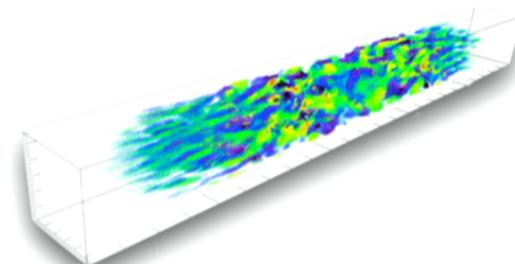


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