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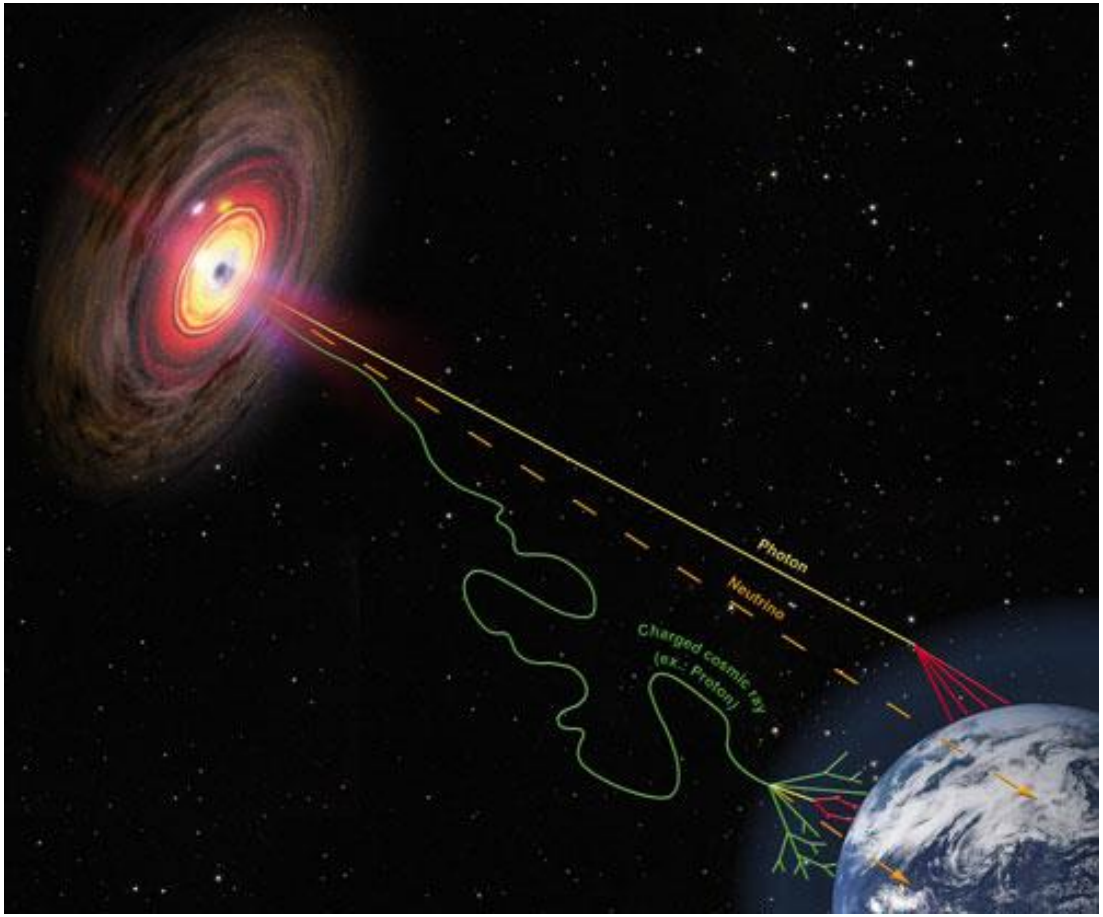
New avenues in Laboratory Astroparticle Physics - Investigating Collisionless Shock Acceleration in Laboratory Experiments

Christian Rödel

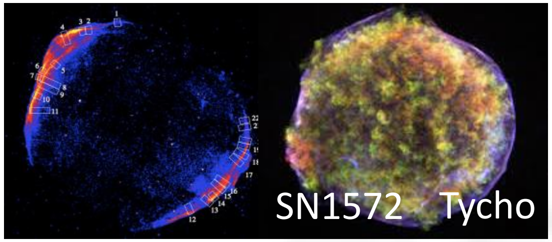
Helmholtz-Institute Jena

EMMI Days, 20.11.2018

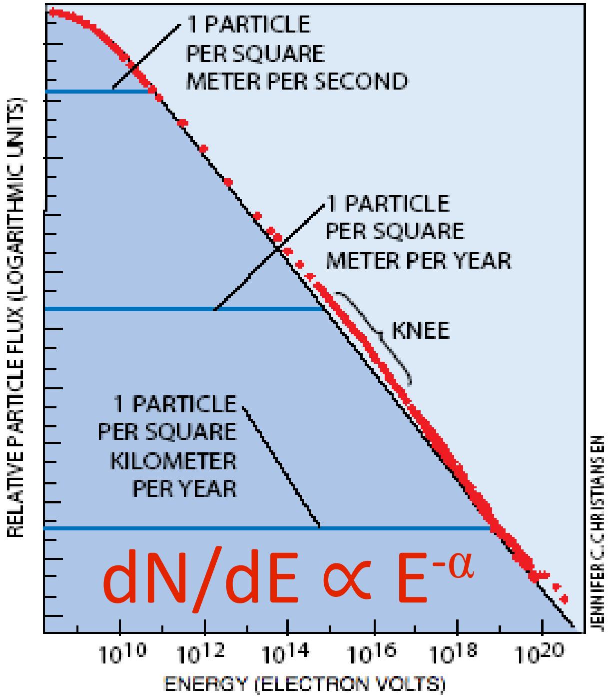
Astroparticle physics: Cosmic rays



Source: Helmholtz Initiative for Astroparticle Physics



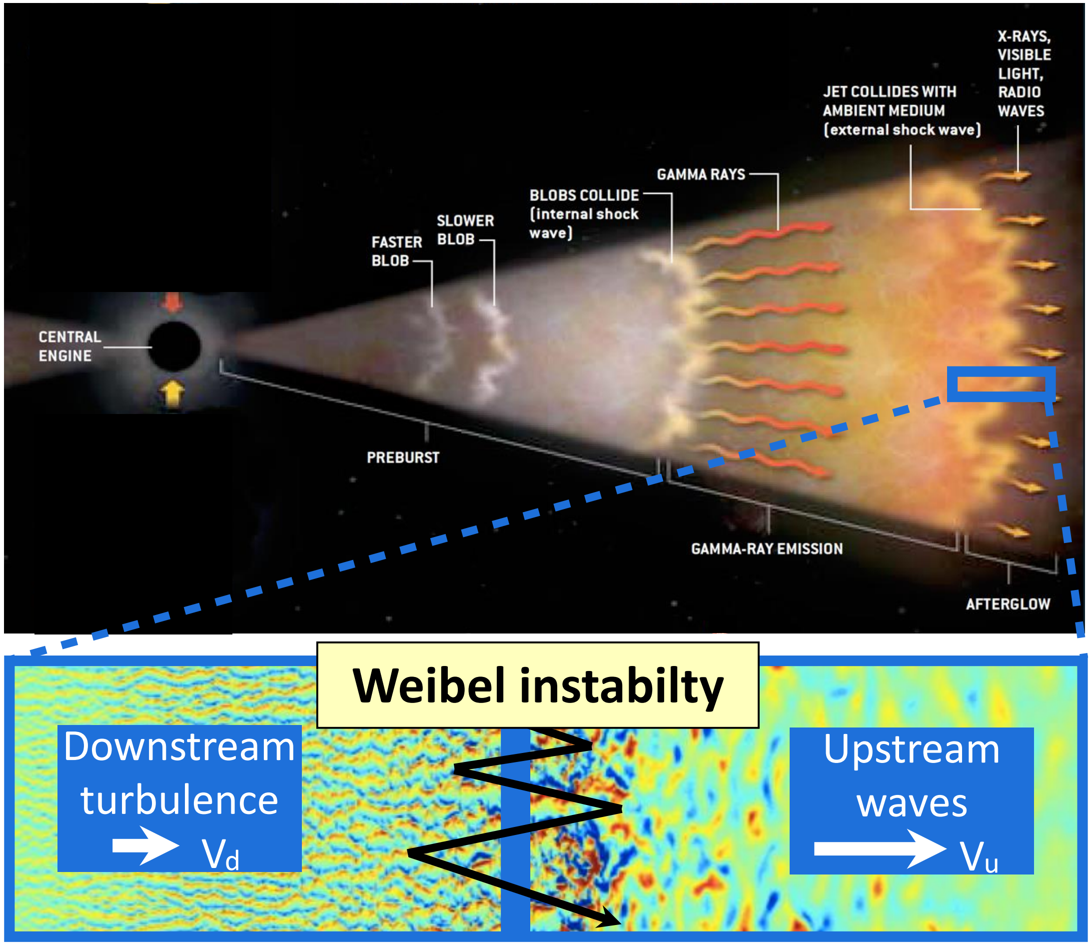
Scientific American, (c) 1998



$$dN/dE \propto E^{-\alpha}$$

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

Particle Acceleration by Collisionless Shocks



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

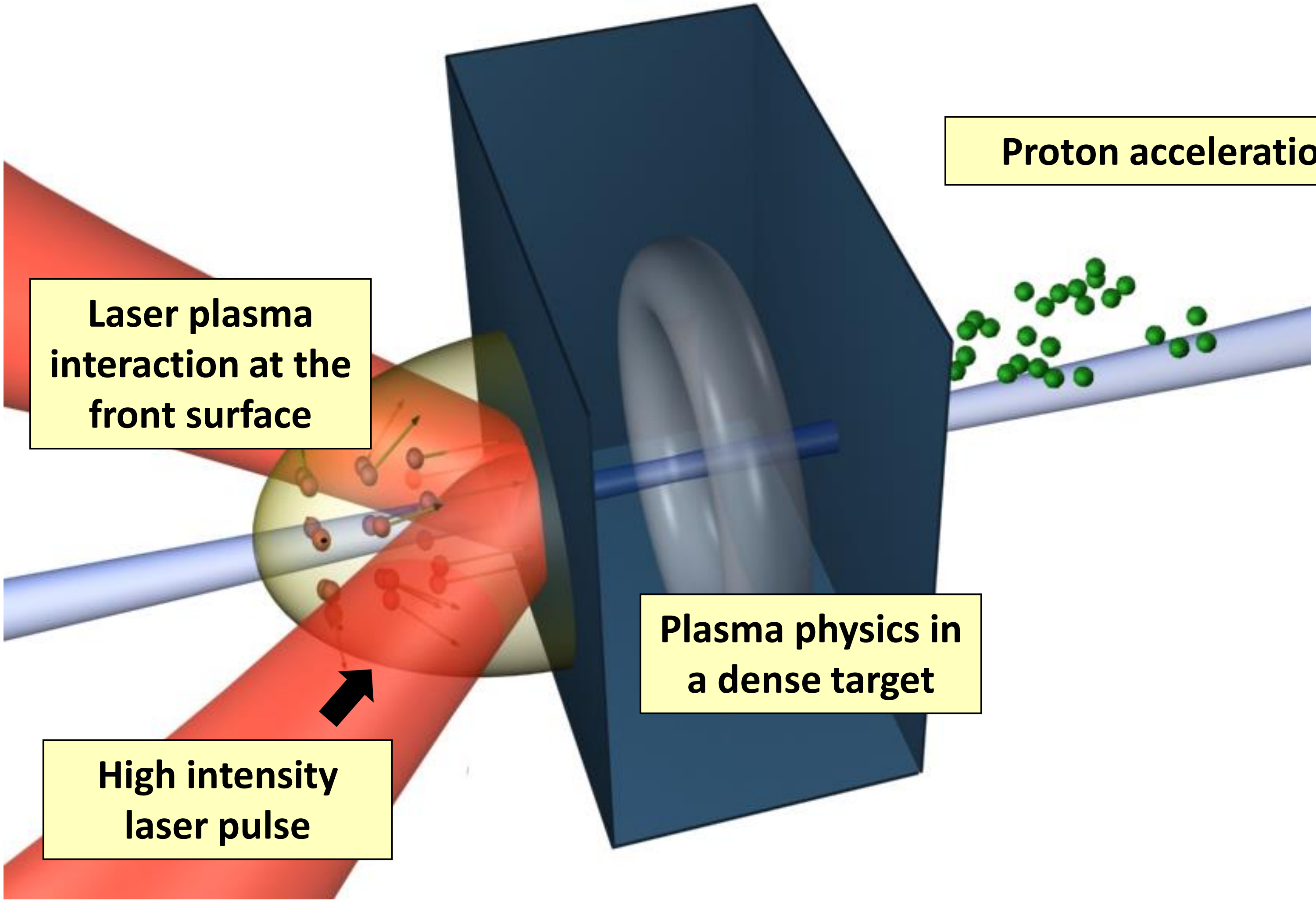
- Understanding of microphysics is gained via plasma theory
- Microphysics of CSA and magnetic field generation has not yet been fully verified by experiments

How can we design experiments to study the microphysics of CSA ?

Outline

1. **Introduction – Collisionless Shock Acceleration and Weibel instability**
2. **High intensity laser plasma interactions**
3. **Experiments using cryogenic hydrogen targets**
   1. Proton acceleration using 150 TW laser DRACO at HZDR
   2. Net-like structure of proton beam profile
   3. Interpretation of proton radiography of Weibel filaments
4. **Summary and outlook**

High intensity laser plasma interactions



Proton acceleration

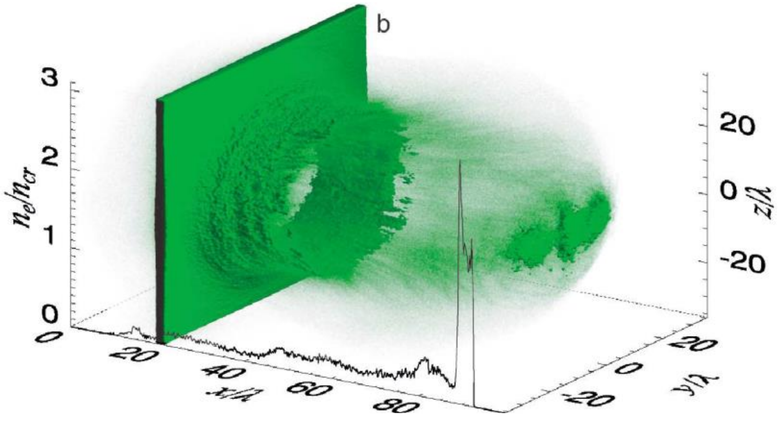
Laser plasma interaction at the front surface

Plasma physics in a dense target

High intensity laser pulse

Laser plasma simulations motivate novel acceleration regimes

Radiation Pressure Acceleration



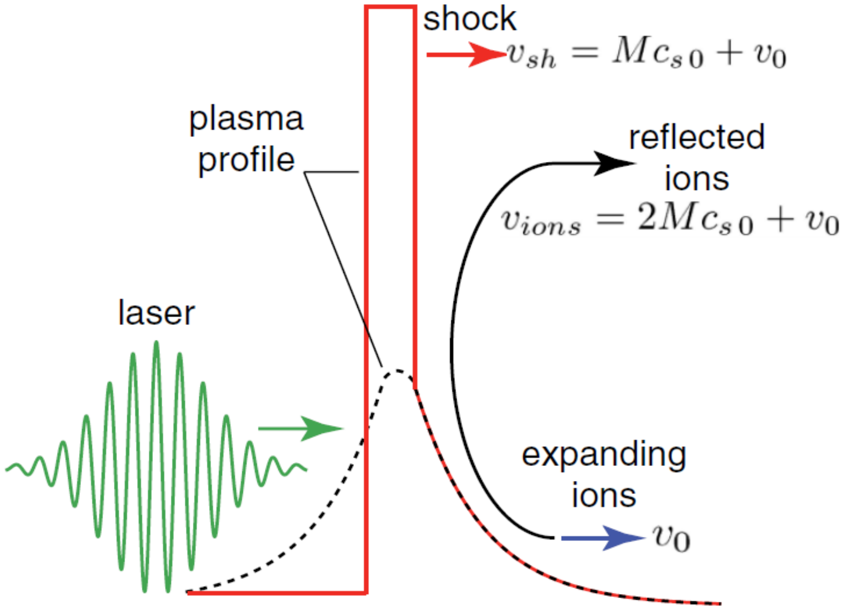
T. Esirkepov et al., Phys. Rev. Lett. (2004)

$$P_{Laser} = \frac{2I}{c} = 300\ \mathrm{Gbar}$$

for $5 \cdot 10^{20}\ \mathrm{W/cm^2}$

Thin targets with low areal mass density are ideal

Collisionless Shock Acceleration

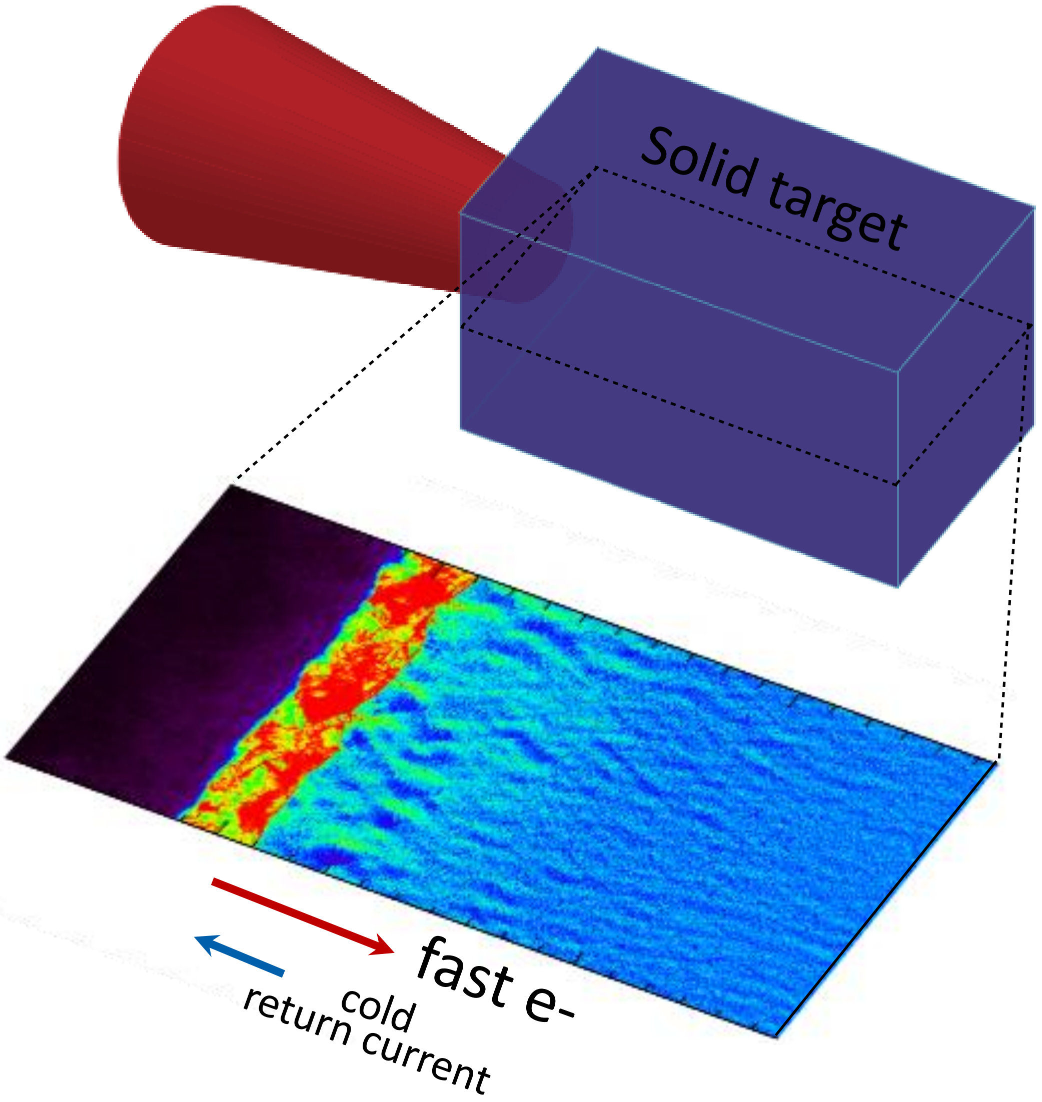


F. Fiuza et al., Phys. Rev. Lett. (2012)

Thick targets containing hydrogen are required

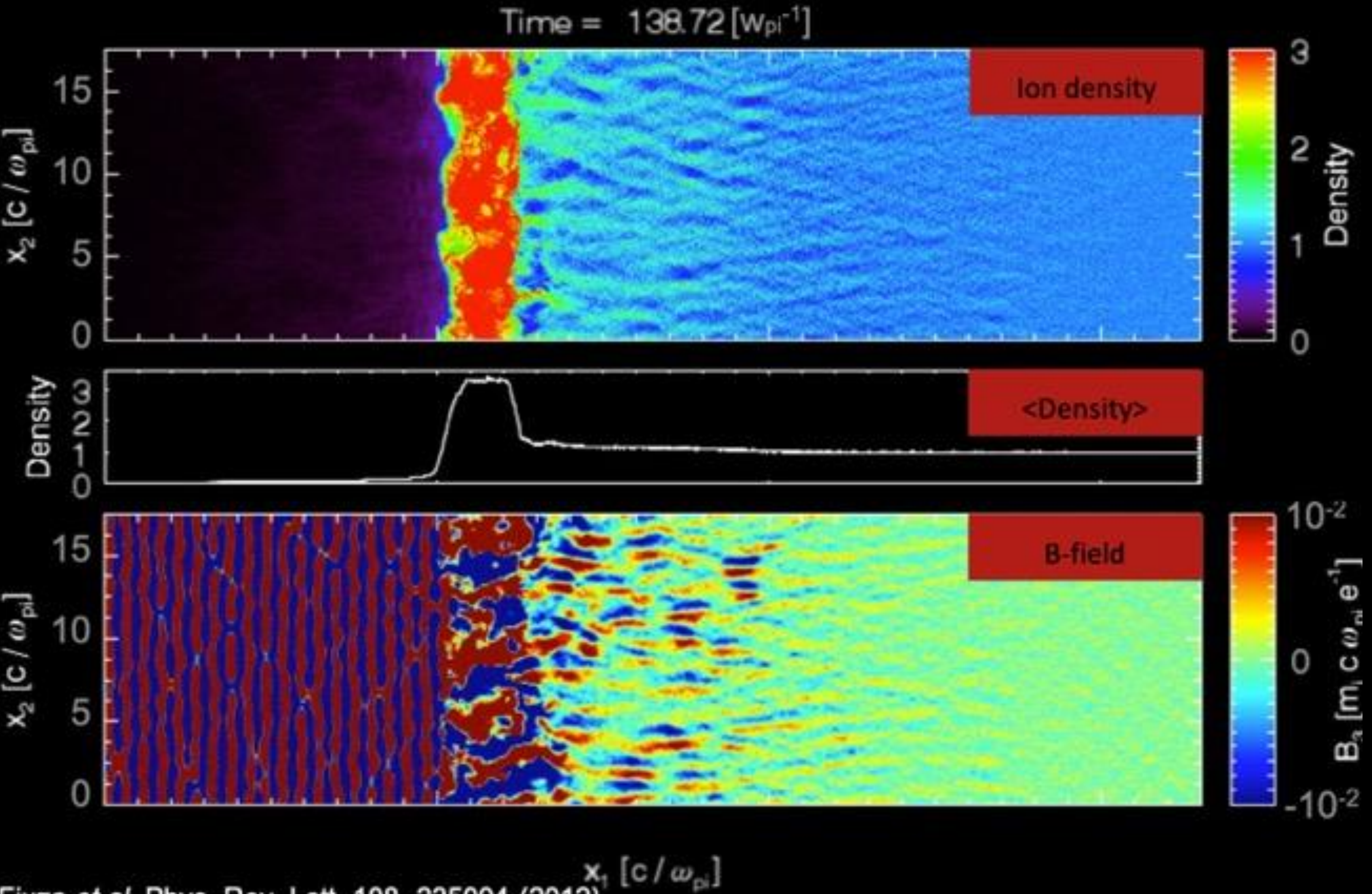
Hydrogen target of solid density would be perfect

Collisionless Shock Acceleration in laser plasma simulations



- **Weibel-mediated Collisionless Shock Acceleration**
- Laser:
  - $\lambda_0 = 1\ \mu m$
  - $I_0 = 10^{20} - 10^{22}\ W/cm^2$
  - $\tau = 1\ ps$
- Plasma:
  - box: $100\ \mu m \times 20\ \mu m$
  - $n_e^0 = 10\, n_c - 100\, n_c$
  - $m_i/m_e = 1836$

F. Fiuza *et al.*,
Phys. Rev. Lett. 108, 235004 (2012)



F. Fiuza *et al.* Phys. Rev. Lett. 108, 235004 (2012)

Outline

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3. **Experiments using cryogenic hydrogen targets**
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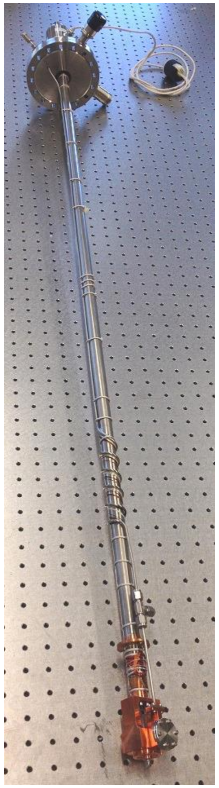
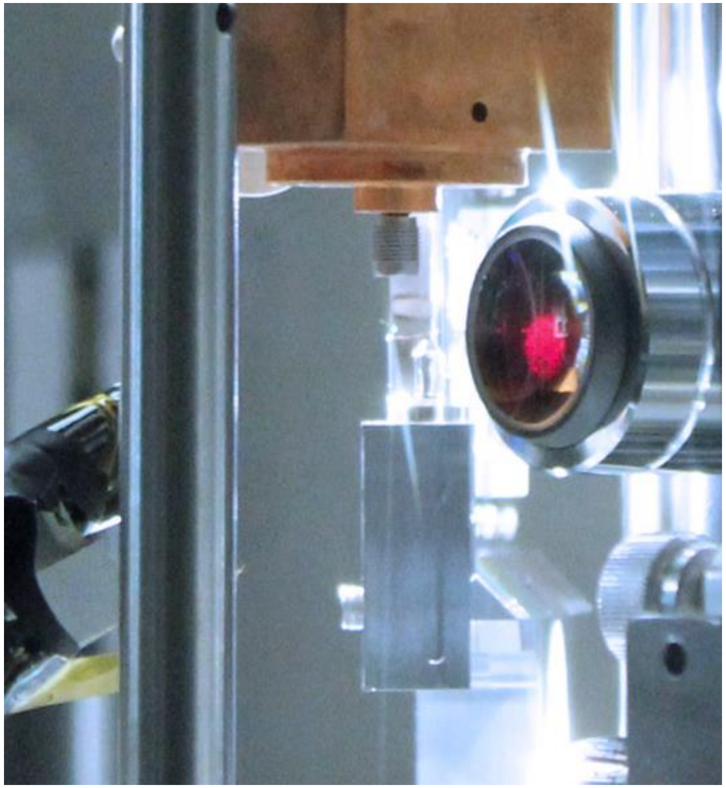
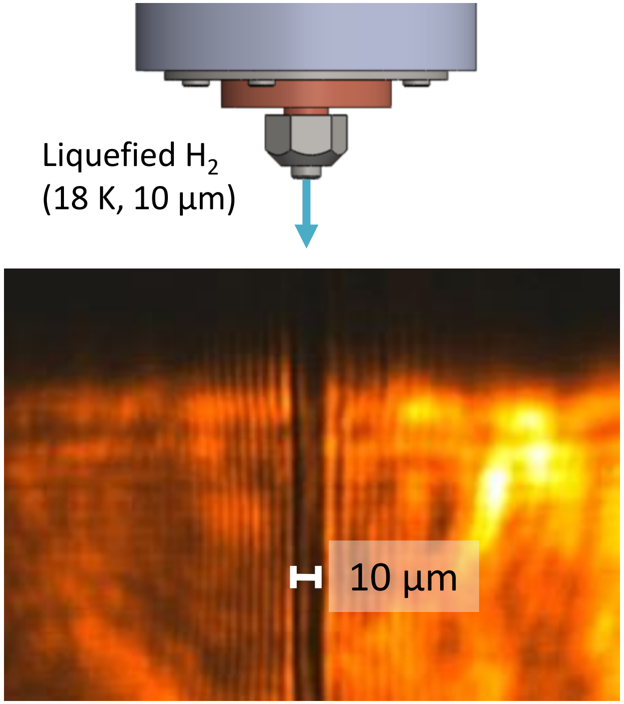
Cryogenic hydrogen jets with cylindrical geometry



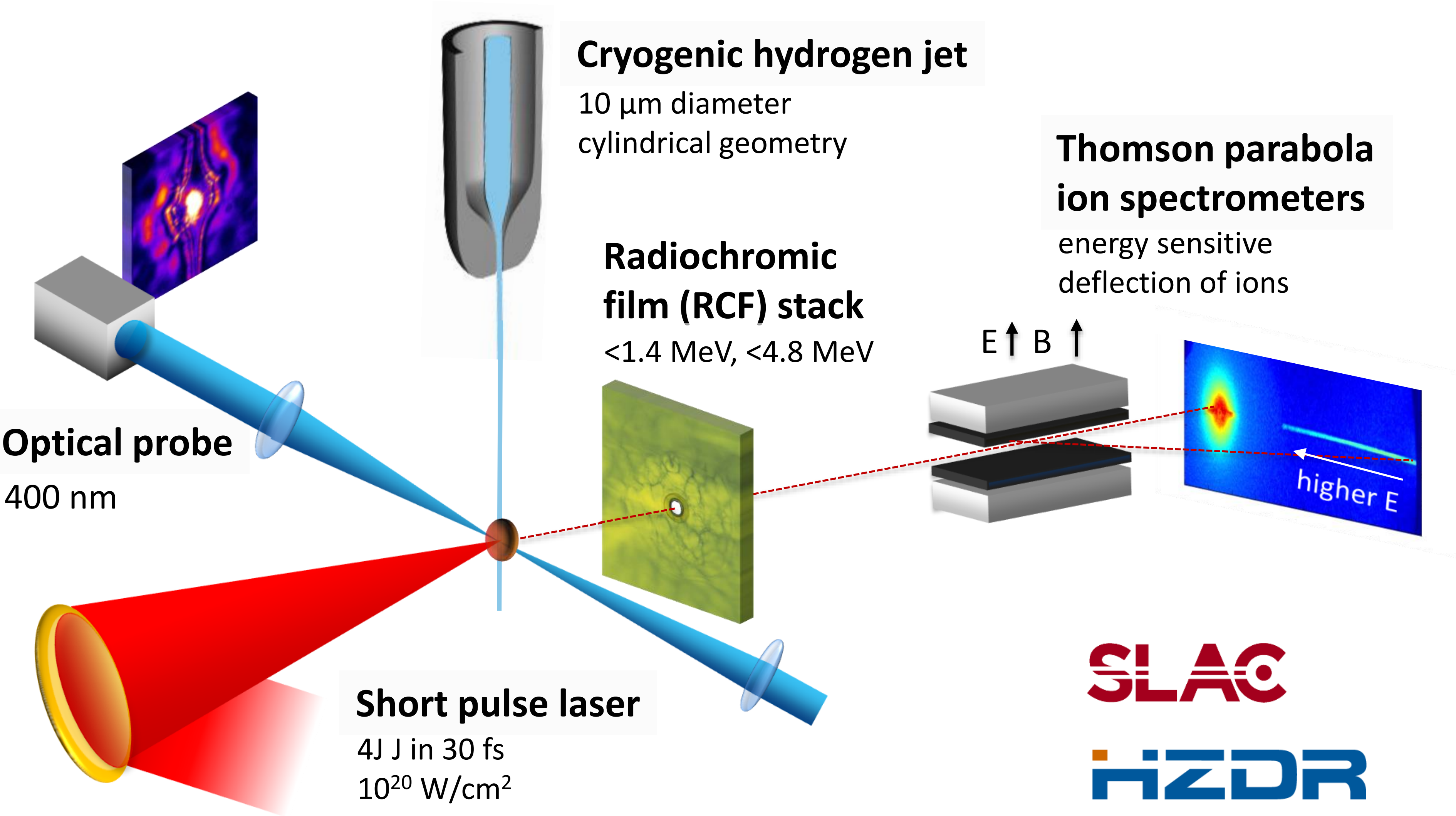




J. Kim, S. Göde, S. Glenzer, Review of Scientific Instruments 87, 11E328 (2016)

Cryogenic hydrogen jet of solid density as target for laser proton acceleration

Experimental setup



Cryogenic hydrogen jet

10 µm diameter
cylindrical geometry

Thomson parabola ion spectrometers

energy sensitive
deflection of ions

Radiochromic film (RCF) stack

<1.4 MeV, <4.8 MeV

Optical probe

400 nm

Short pulse laser

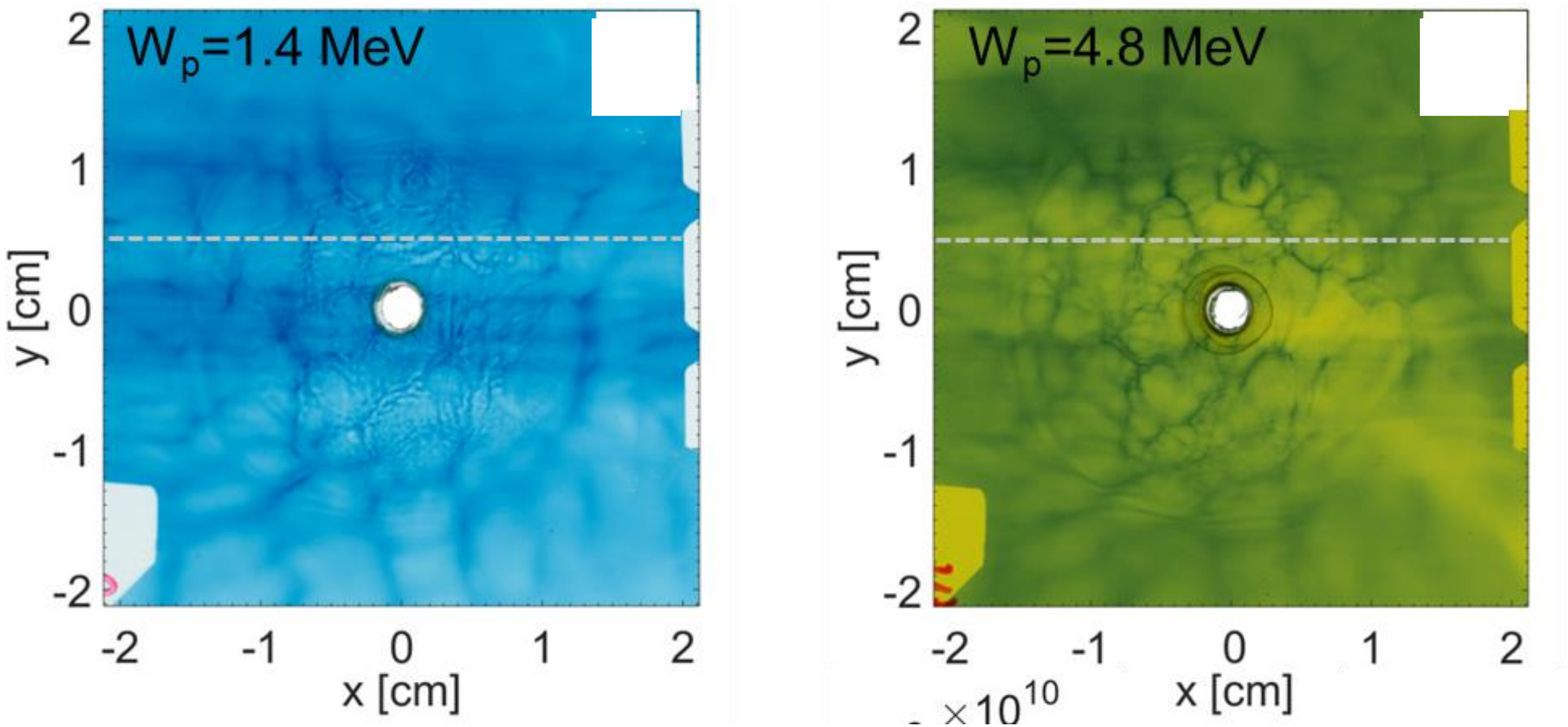
4J J in 30 fs
10^{20} W/cm^2

SLAC

HZDR

Proton beam profiles

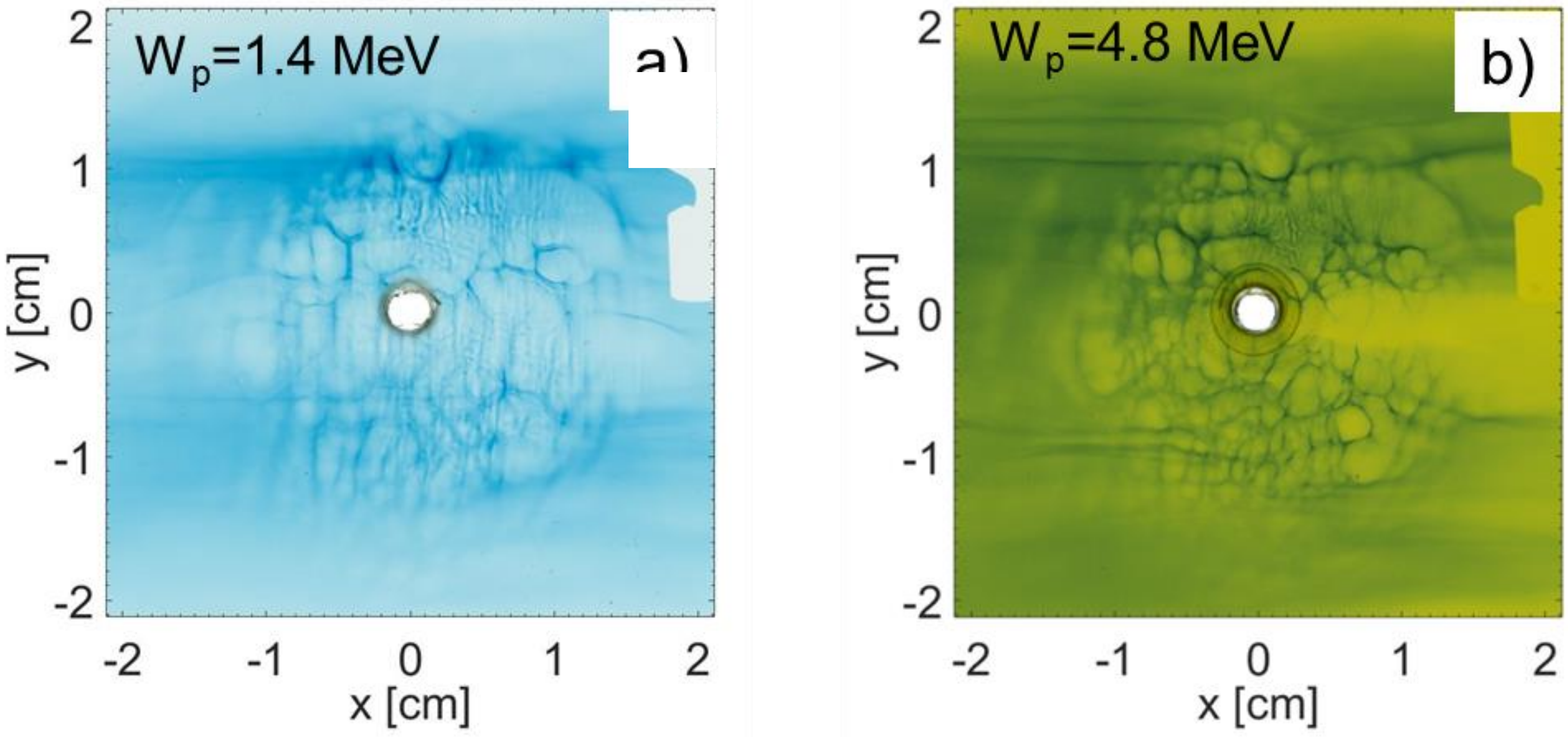
5 µm hydrogen target



Net-like modulations in proton beam

Proton beam profiles

10µm hydrogen target



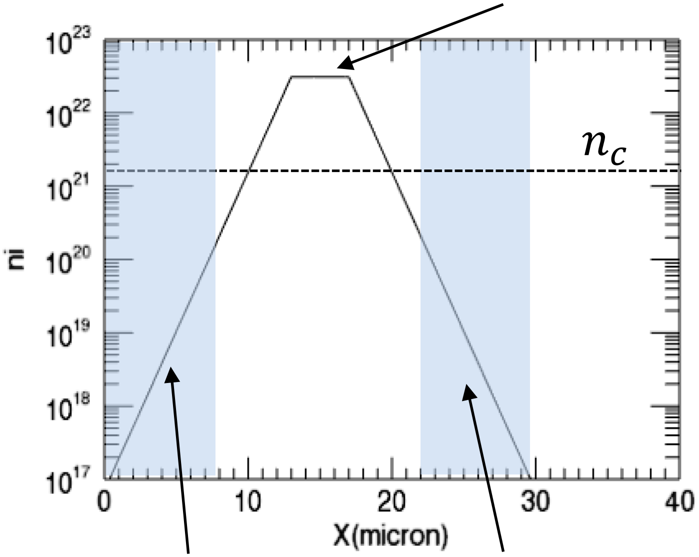
Net-like modulations in proton beam

Interpretation of experimental results

Optical probe data can be used to model the plasma density profile

Solid density of hydrogen

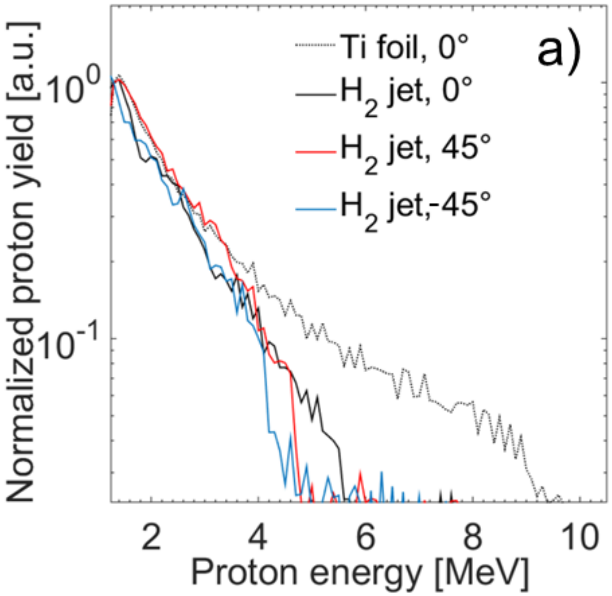
$\rho_{H2} = 0.08$ g/cc corresponds to $n_{max} \simeq 30\, n_c$



Plasma scale length $L_p \simeq 2\ \mu m$

Density profile in undercritial plasma
No insight into overcritical plasma

Spectrometer shows low proton energies

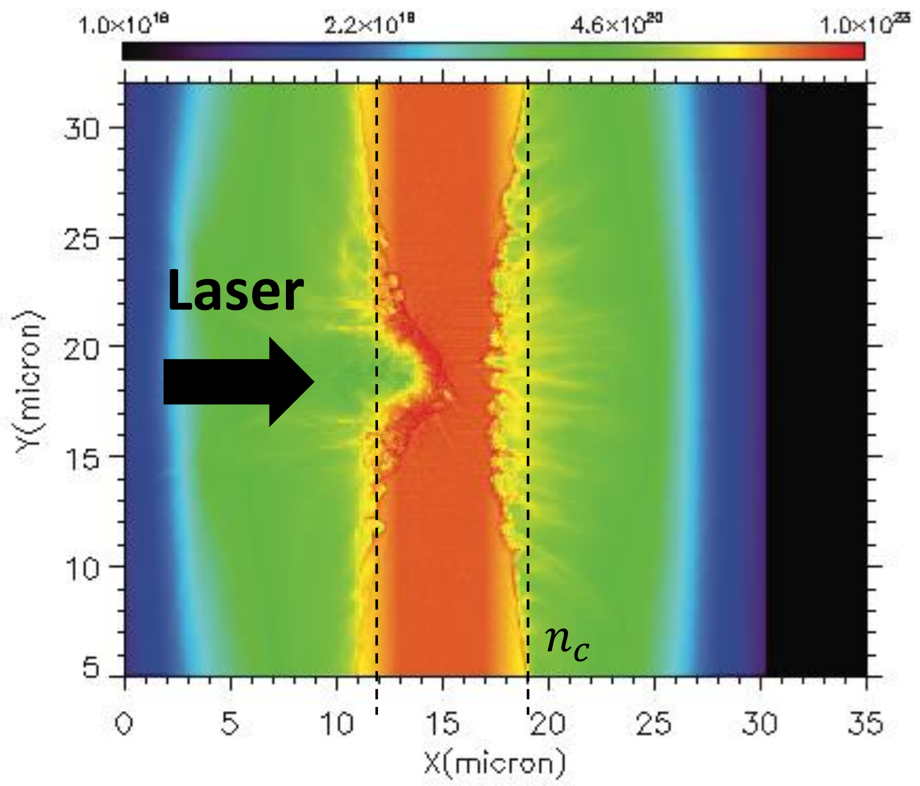


Can be explained by the 2 µm plasma density gradient

M. Kaluza, J. Schreiber et al., Phys. Rev. Lett. (2006)

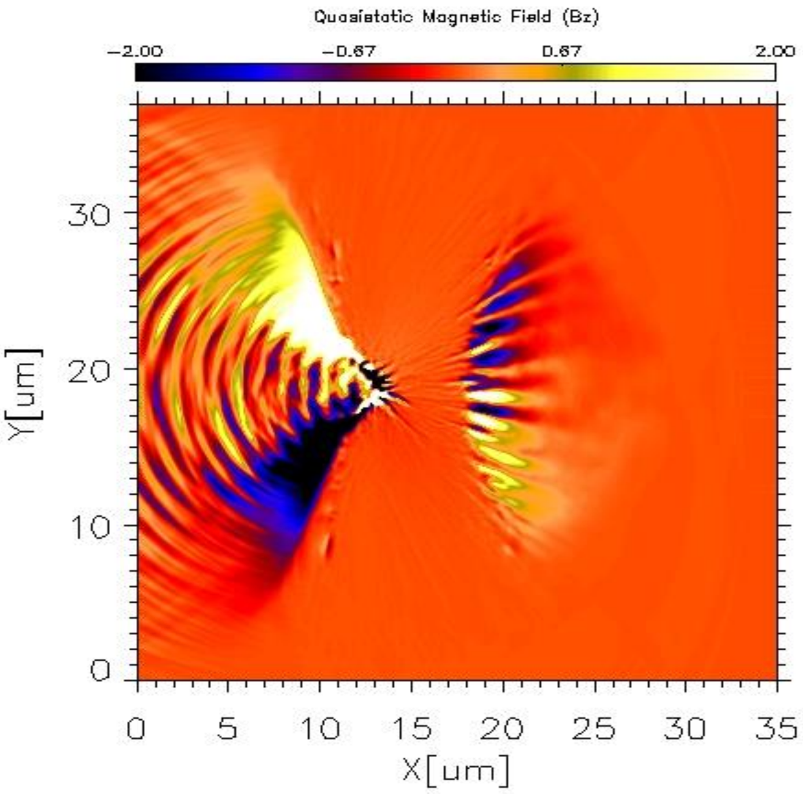
2D Laser plasma simulation

Plasma density (protons)



Filamentation of plasma density in the rear-side density gradient

B_z field

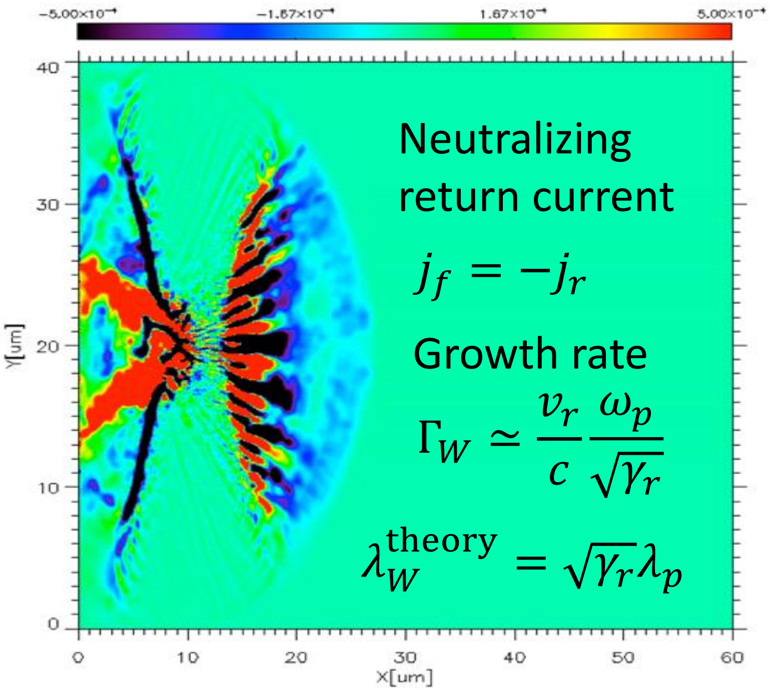


Alternating B_z-field (110 MG) in the rear-side plasma density gradient

Simulations by R. Mishra / SLAC

2D Laser plasma simulation

Current density at 100 fs



Neutralizing return current

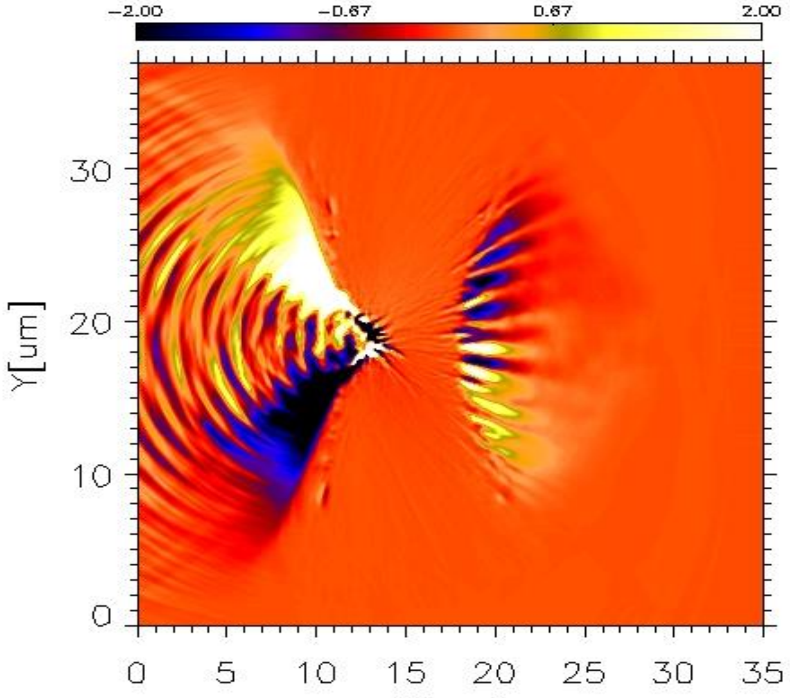
$$j_f = -j_r$$

Growth rate

$$\Gamma_W \simeq \frac{v_r}{c}\frac{\omega_p}{\sqrt{\gamma_r}}$$

$$\lambda_W^{\text{theory}} = \sqrt{\gamma_r}\lambda_p$$

B_z field at 100 fs

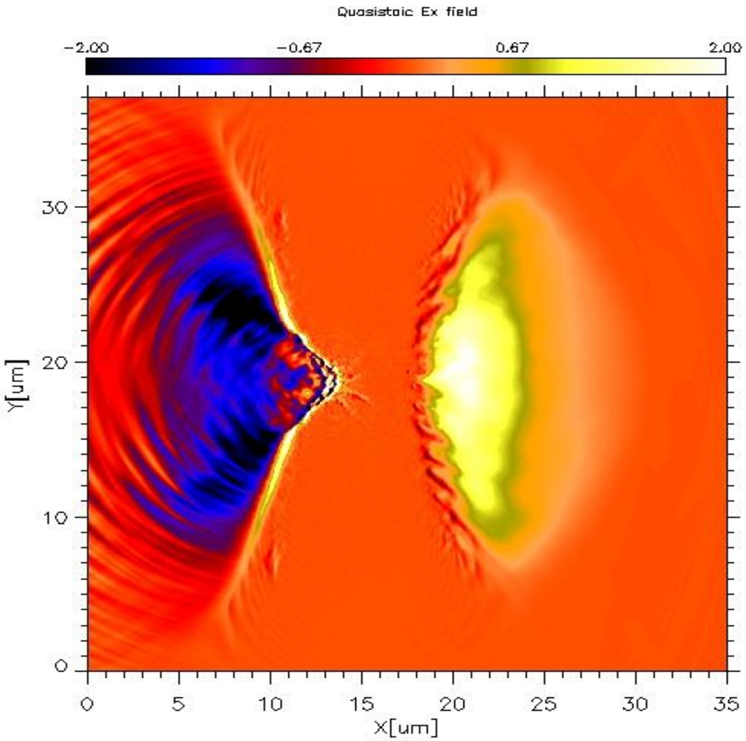


Weibel filamentation in overdense plasmas
No direct experimental observation so far

Details and analytical modelling in: S. Göde, C. Rödel, K. Zeil et al., Phys. Rev. Lett. (2017)

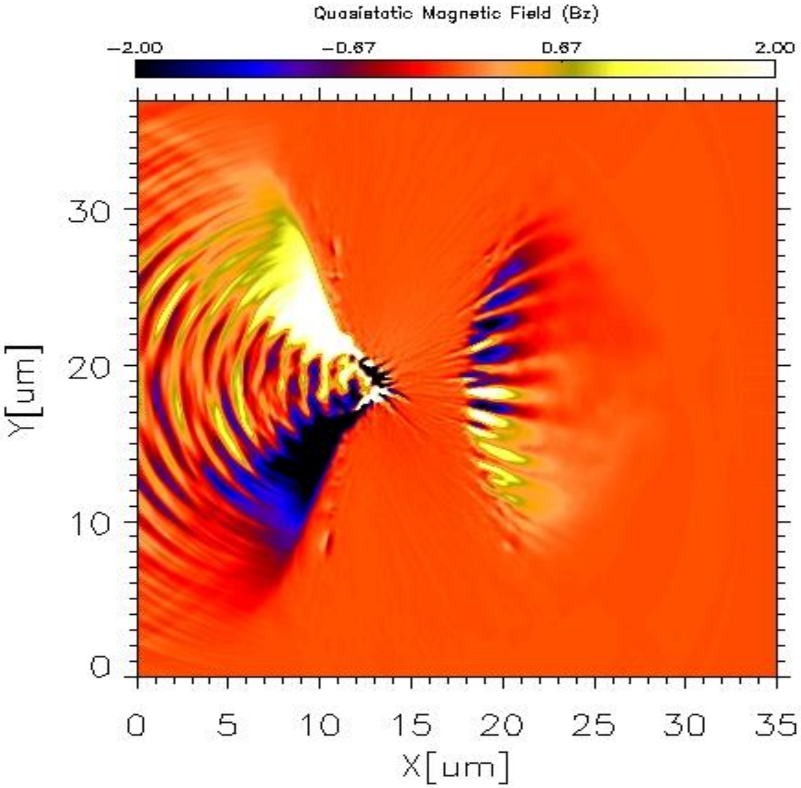
2D Laser plasma simulation

E_x field at 100 fs



TNSA sheath field is present in the plasma density gradient

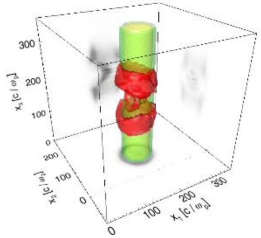
B_z field at 100 fs



Accelerated proton beams deflected by MG magnetic fields

Proton radiography of self-generated B fields

Simulated proton beam profile in the detector plane

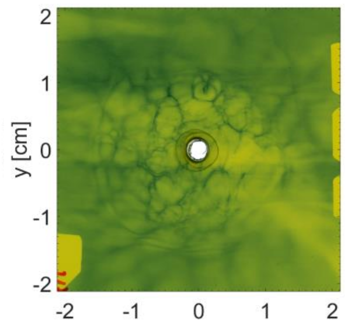


Ballistic propagation →

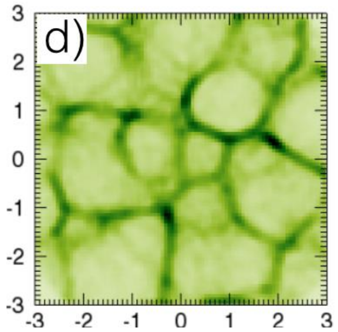
Protons from 3D simulations
(x_i, p_i), > 1MeV

Proton beam profile in
detector plane

Measured proton beam profile



Protons from rear side

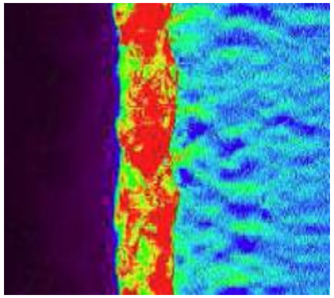


Good qualitative agreement to 3D simulations

Bubble-like structure of TNSA protons

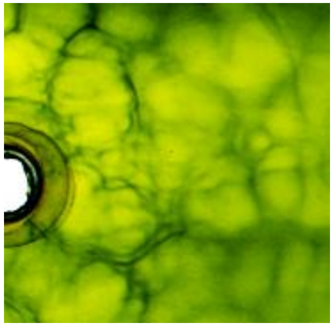
Summary

1. **Laser plasma simulations suggest the investigation of CSA and relativistic streaming instabilities using high intensity laser interactions with solid-density hydrogen targets**



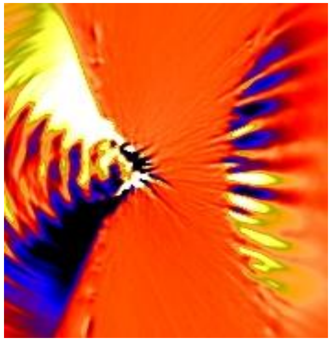
2. **Laser plasma experiments**
   - Solid-density hydrogen targets for laser proton acceleration
   - Observation of modulated proton beams due to Weibel filaments

Challenges: Higher intensities, petawatt pulses required



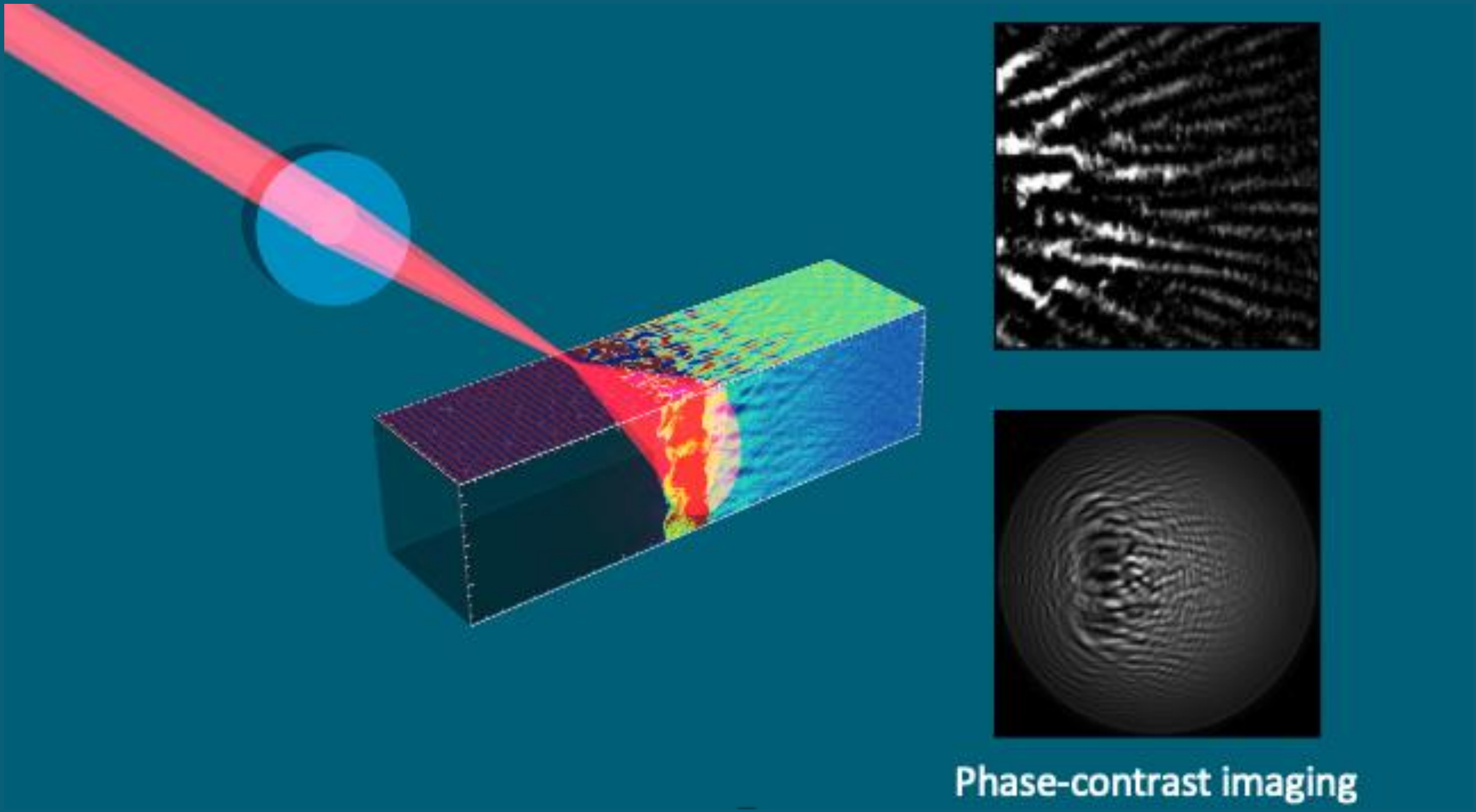
3. **Laser plasma simulations:**
   - 3D PIC simulations show filamentation by Weibel instability in rear-side plasma density gradients

Challenges: Time-resolved measurements of formation of plasma instabilities and collisionless shocks



Outlook:
Observation of collisionless shocks and plasma instabilities using x-ray free-electron lasers

Reconstructed density profile



Thank you for your attention !

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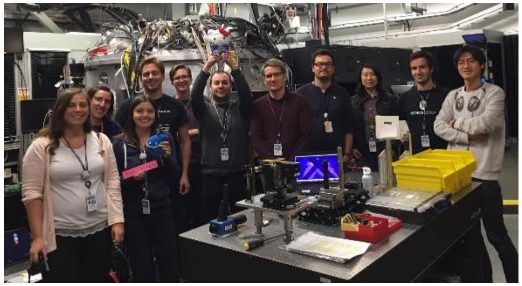

Supplementary slides

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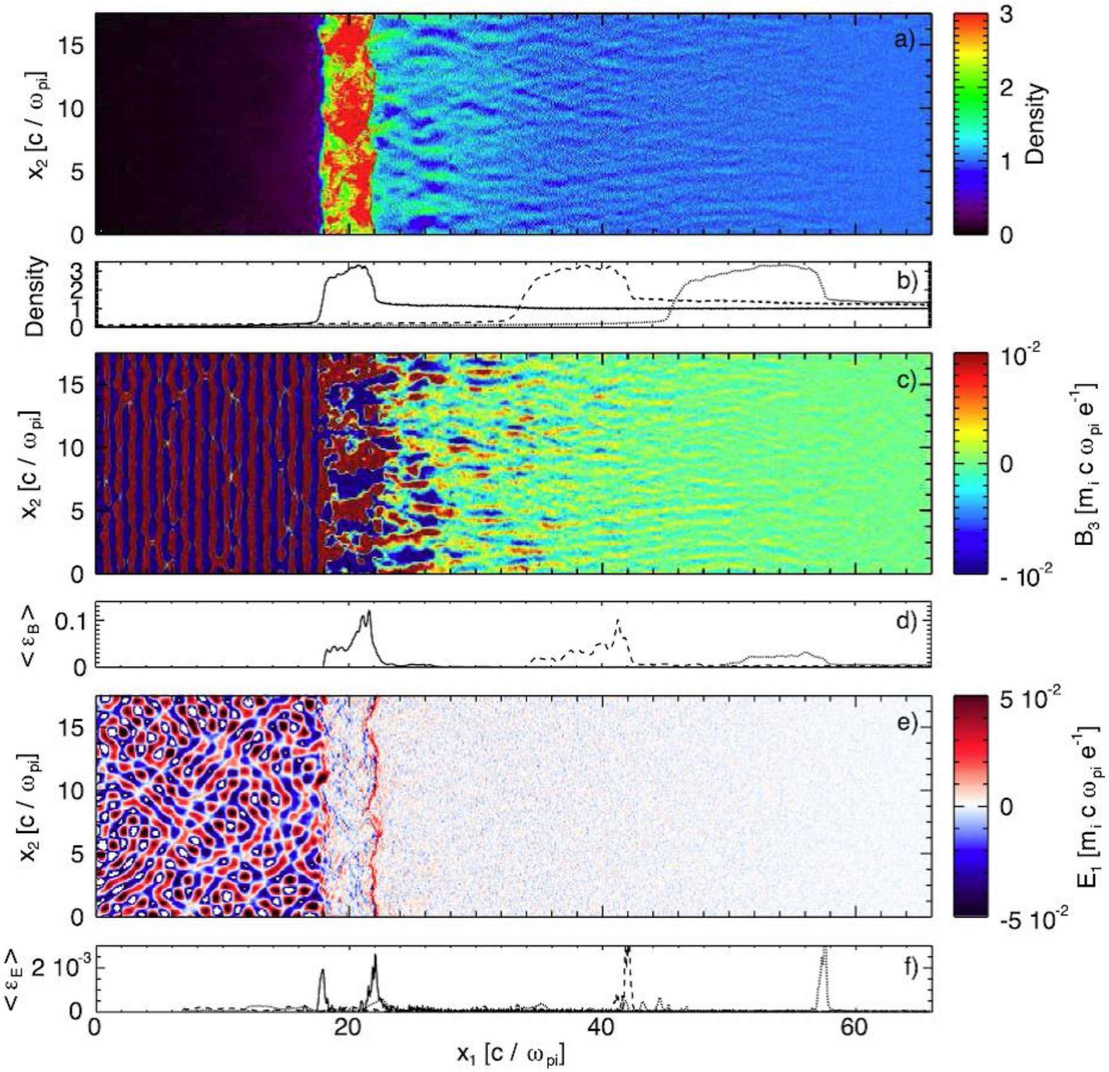

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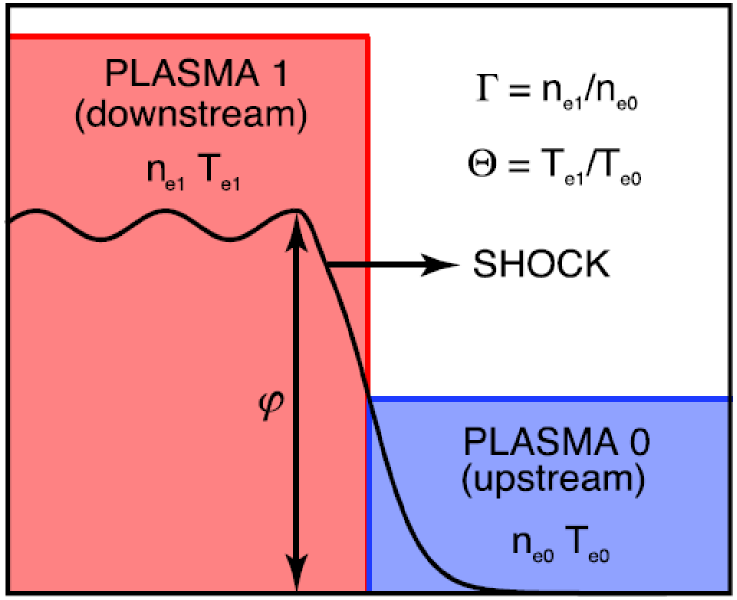
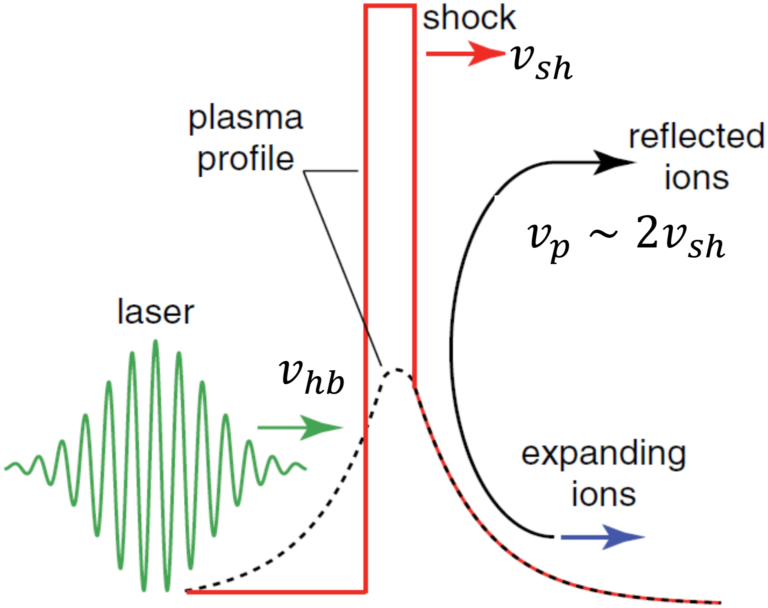
Collisionless Shock Acceleration

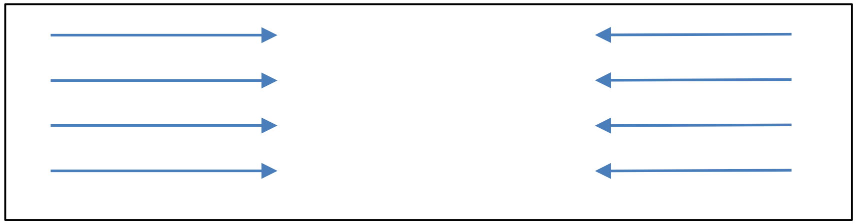




Magnetic field generation by Weibel instability

Weibel instability

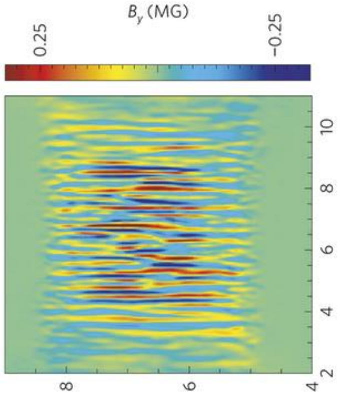
Current filamentation instability



$$\vec{j_G} = 0$$

E. Weibel, Phys. Rev. Lett 2, 83 (1959)
B. D. Fried, Phys. Fluids 2, 337 (1959)

Particle-in-cell simulations



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