Laser-driven proton acceleration from cryogenic hydrogen jets

new prospects in tumor therapy and laboratory astroparticle physics

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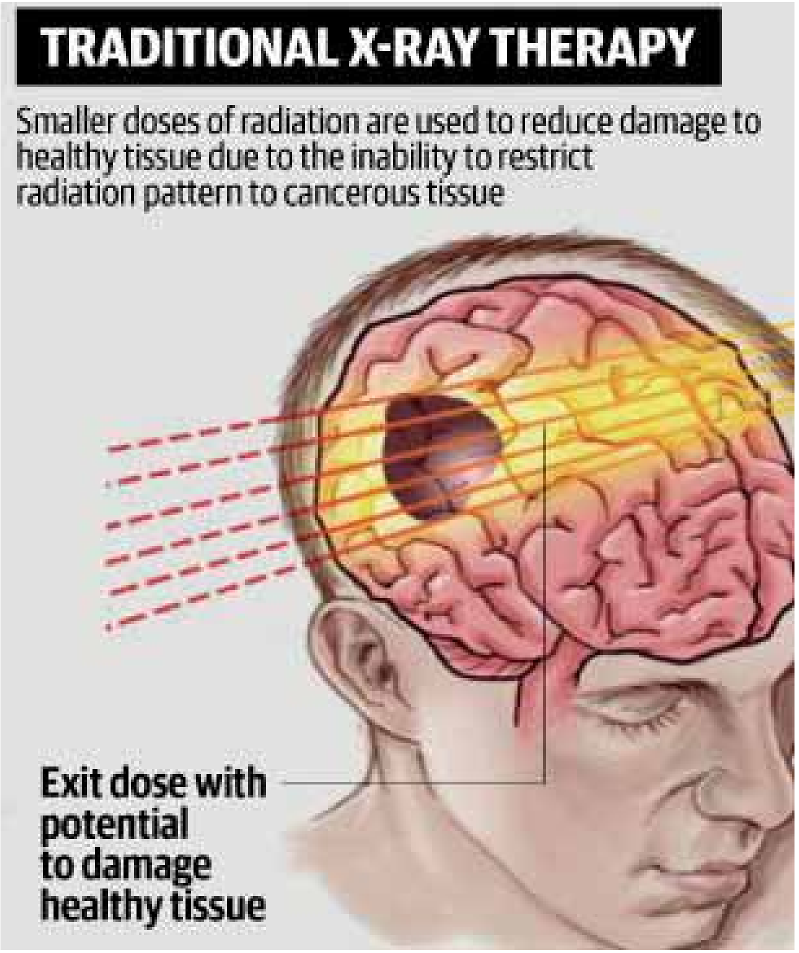
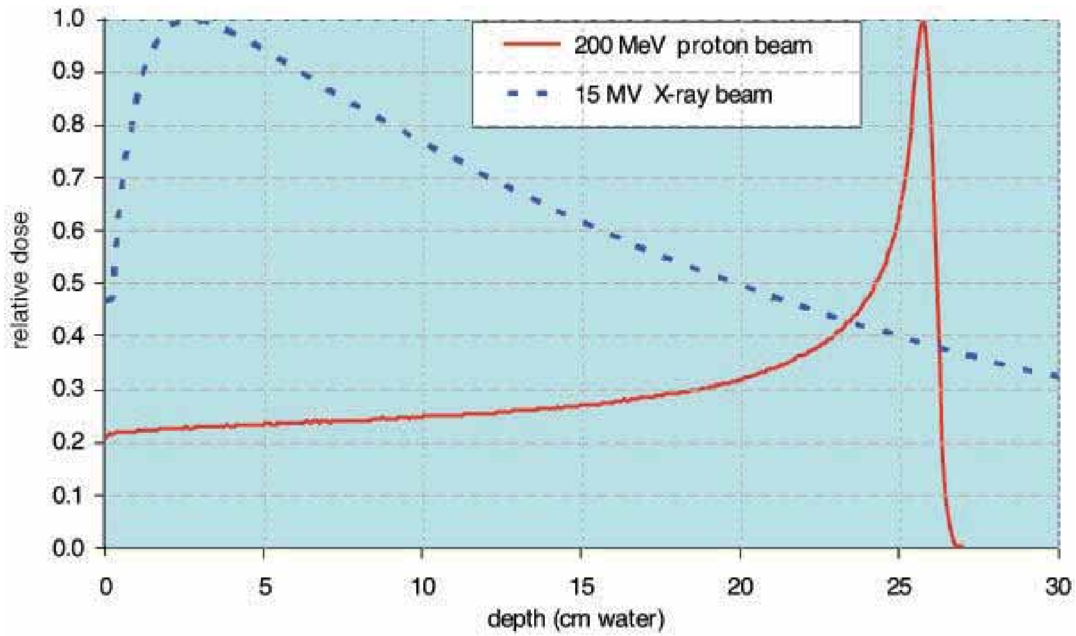
HZDR

U.S. DEPARTMENT OF ENERGY
Office of Science

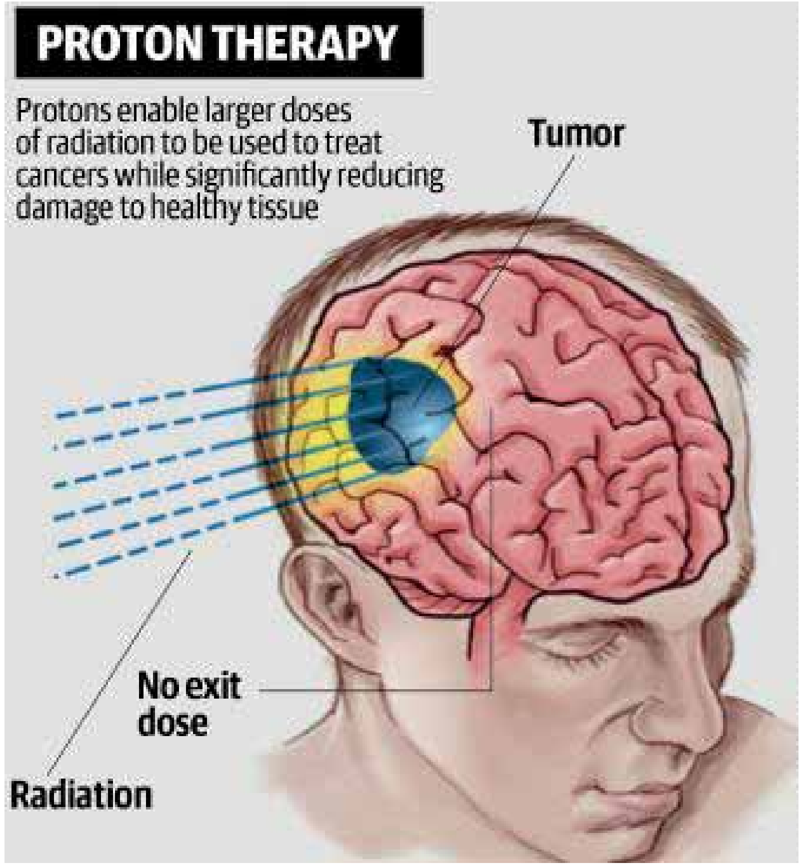
Motivation – laser driven proton acceleration

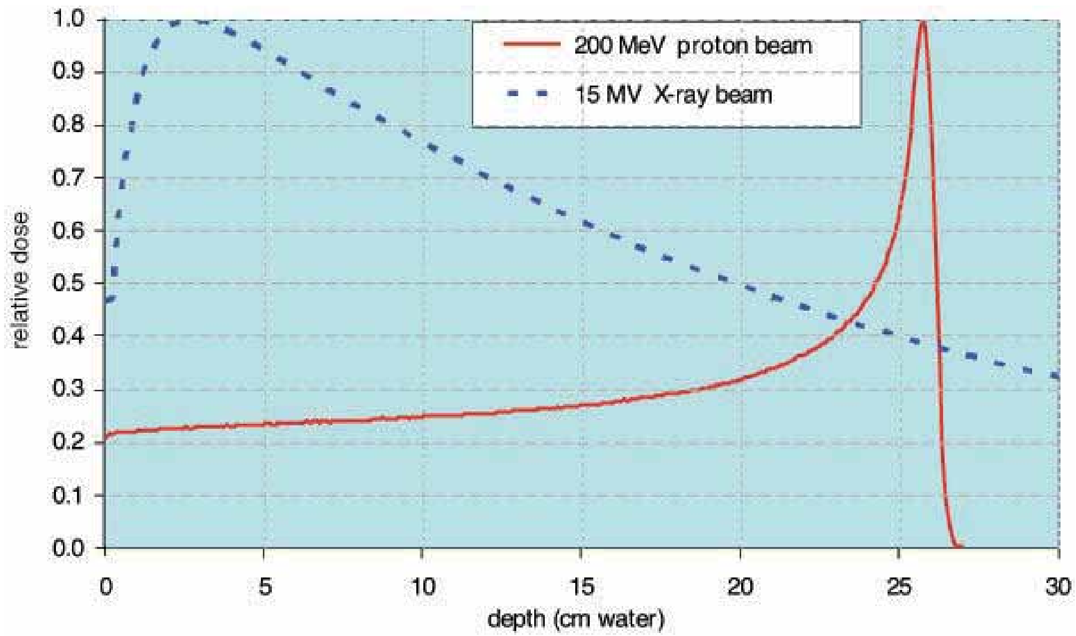




- Ion beam therapy
  - Bragg peak
  - 200 MeV protons are stopped in 25 cm

Motivation – laser driven proton acceleration

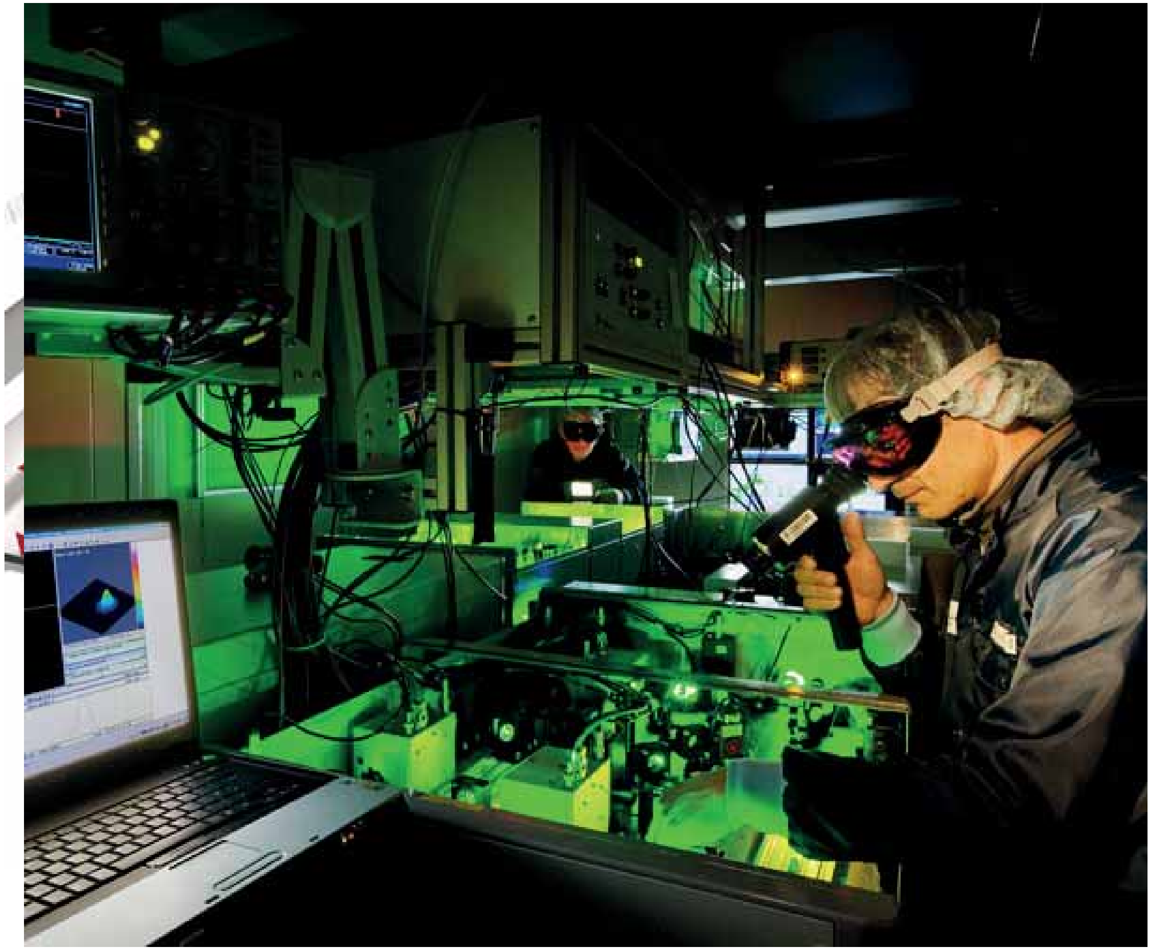




- Ion beam therapy
  - Bragg peak
  - 200 MeV protons are stopped in 25 cm

Small bandwidth, 200 MeV protons beams are required

Motivation – laser driven proton acceleration



- Proton therapy using conventional ion accelerators
  - Large scale facilities
  - Cost: 120 M€
- Laser-driven proton acceleration
  - Target Normal Sheath Acceleration (TNSA)

compact laser system ✓
reduced costs ✓
proton energies are too low ✗
broadband spectrum ✗
single shot proton source ✗
multispecies ion acceleration ✗

K. Zeil

U. Schramm

HZDR

Motivation – High Energy Density Science at SLAC

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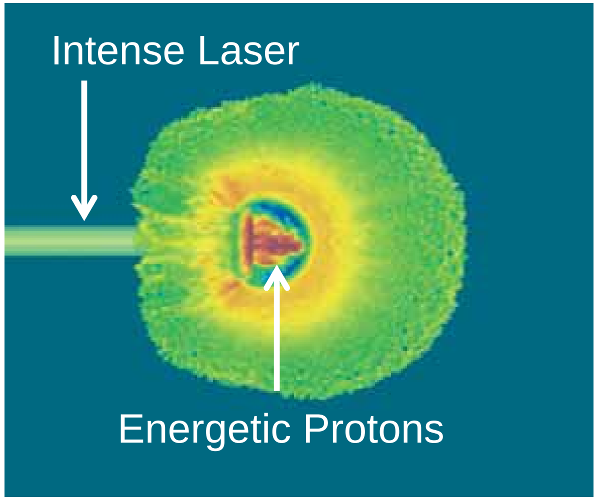
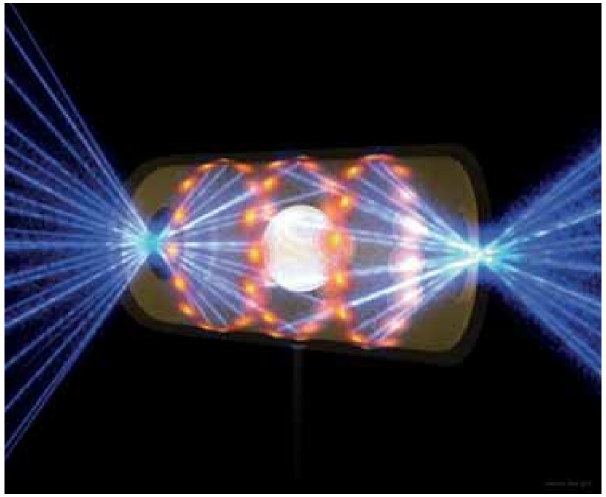
Particle Acceleration



C. Roedel

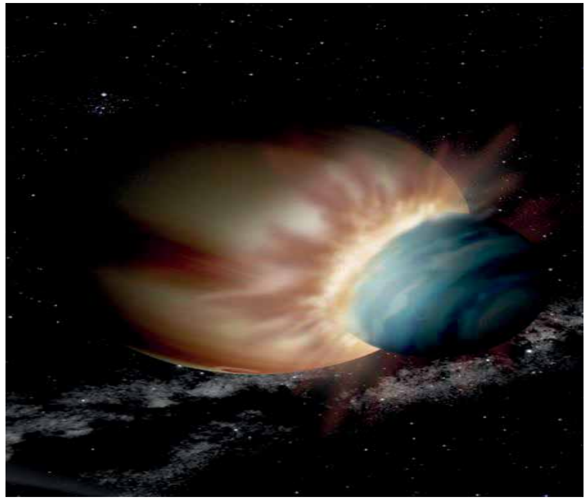
M. Gauthier

Laboratory Fusion



S. Glenzer

Laboratory Astrophysics



F. Fiuza

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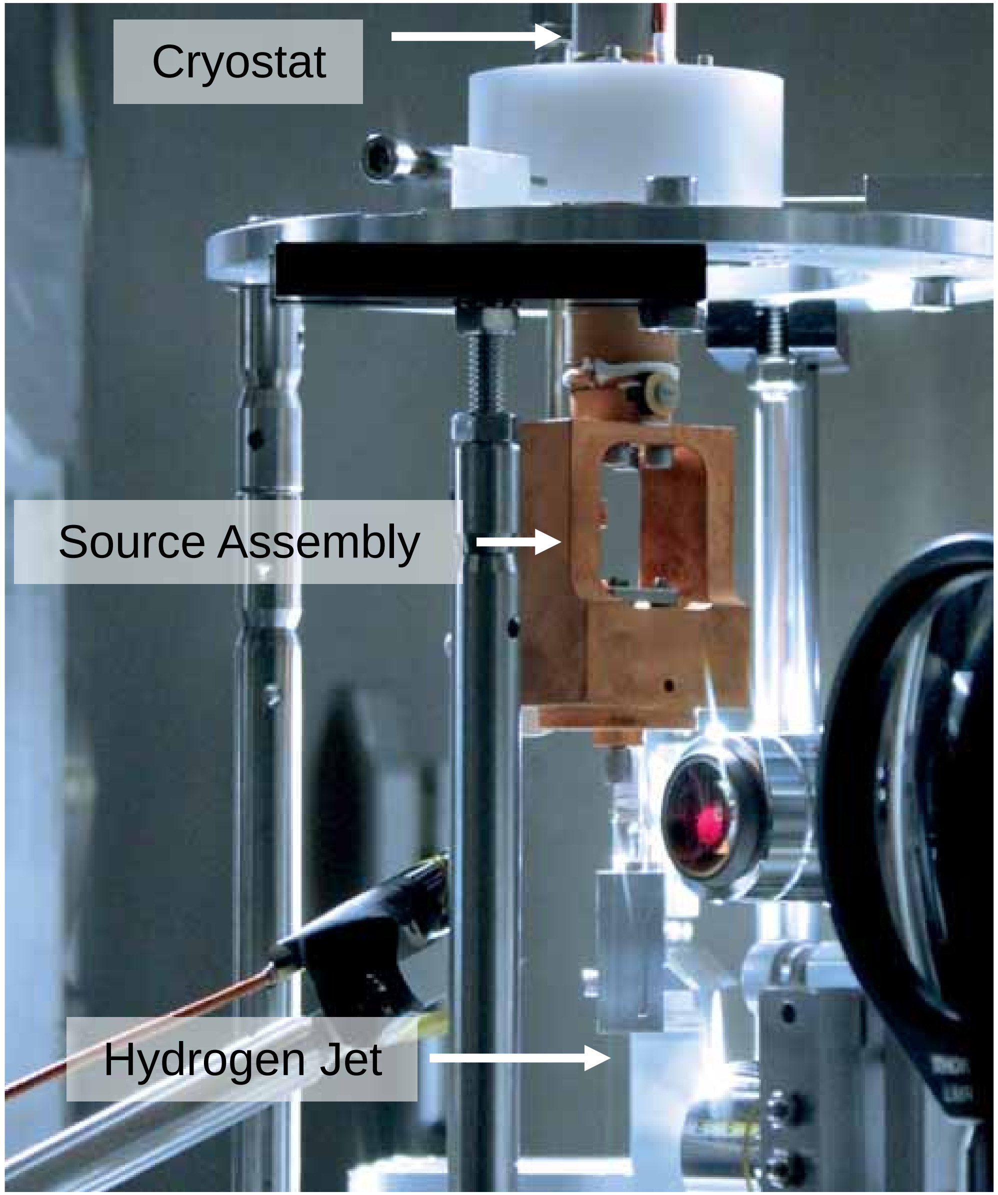
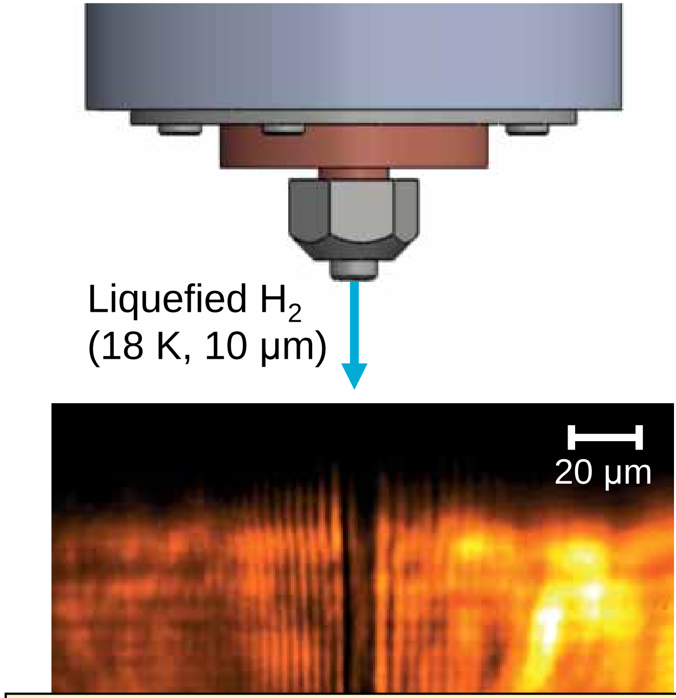
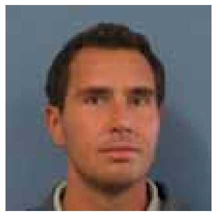
Pure hydrogen target of solid density would be perfect !!!

A cryogenic hydrogen jet for HED experiments





Cylindrical solid-density hydrogen target ✔



S. Goede

A cryogenic hydrogen jet for proton acceleration experiments

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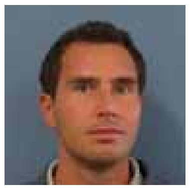
K. Zeil

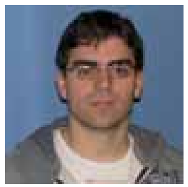
U. Schramm

HZDR



S. Goede

C. Roedel



M. Gauthier

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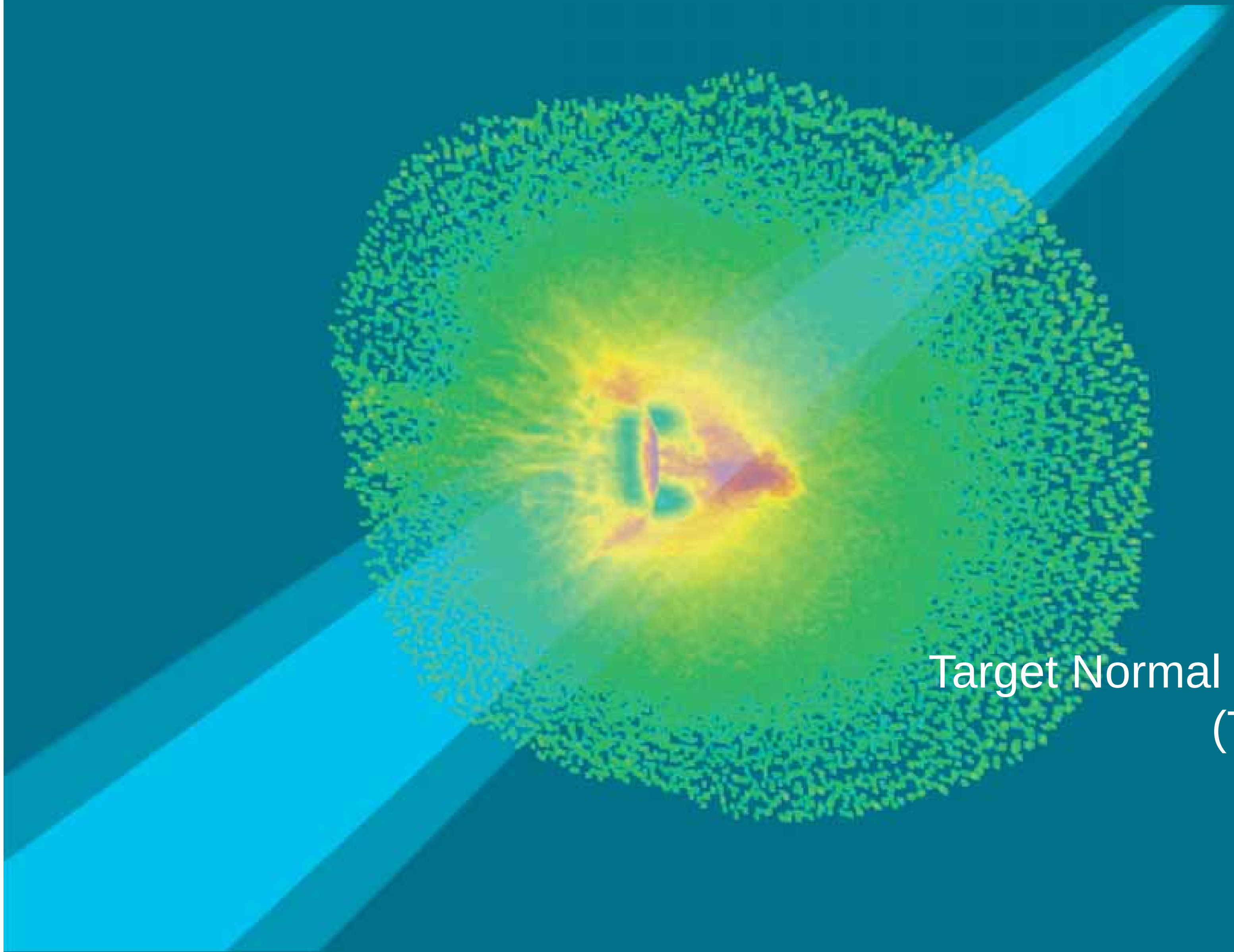
Proton acceleration from solid-density hydrogen jets

Hydrogen jet

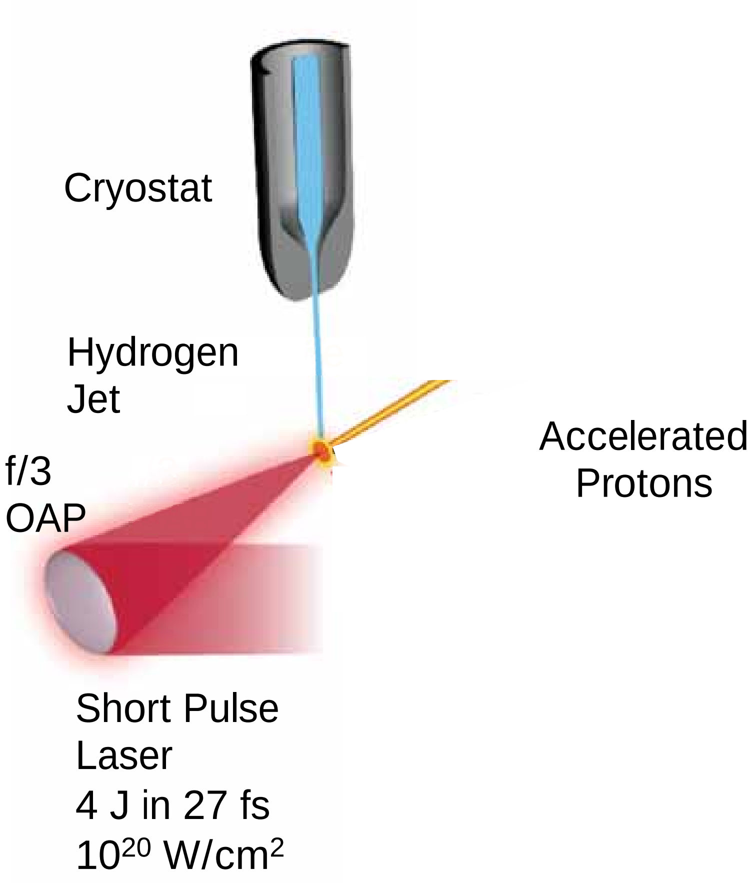
Proton acceleration from solid-density hydrogen jets

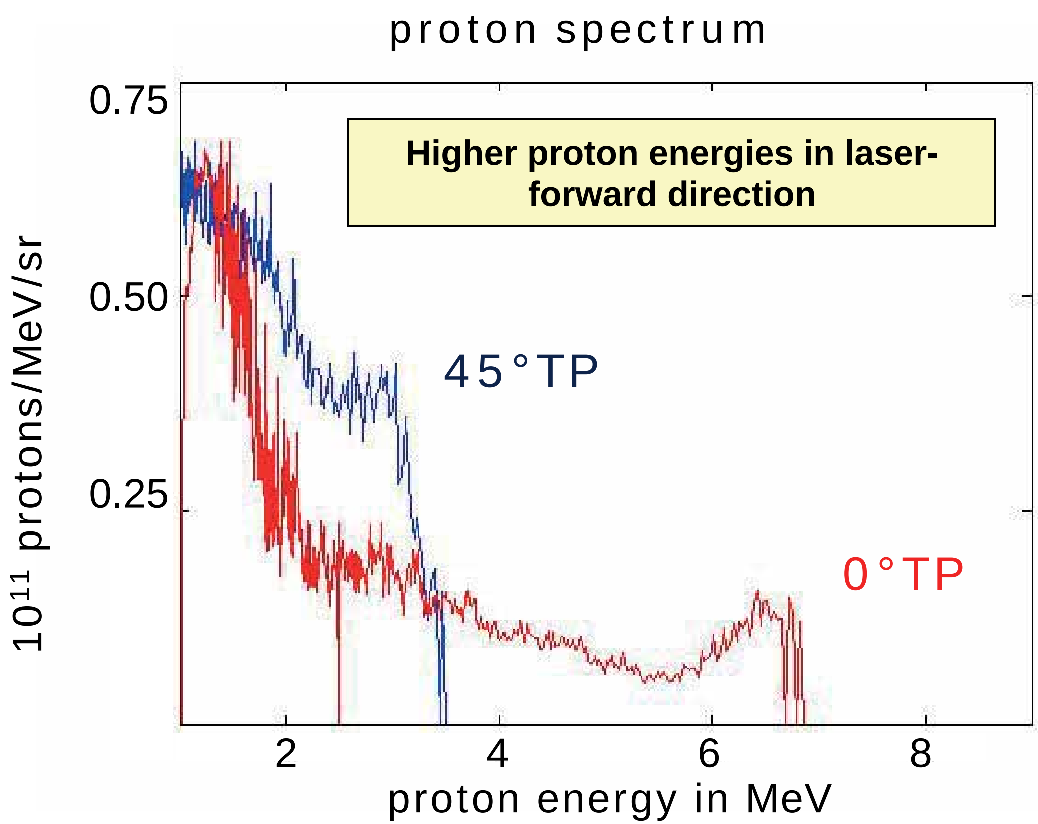
Proton Beams



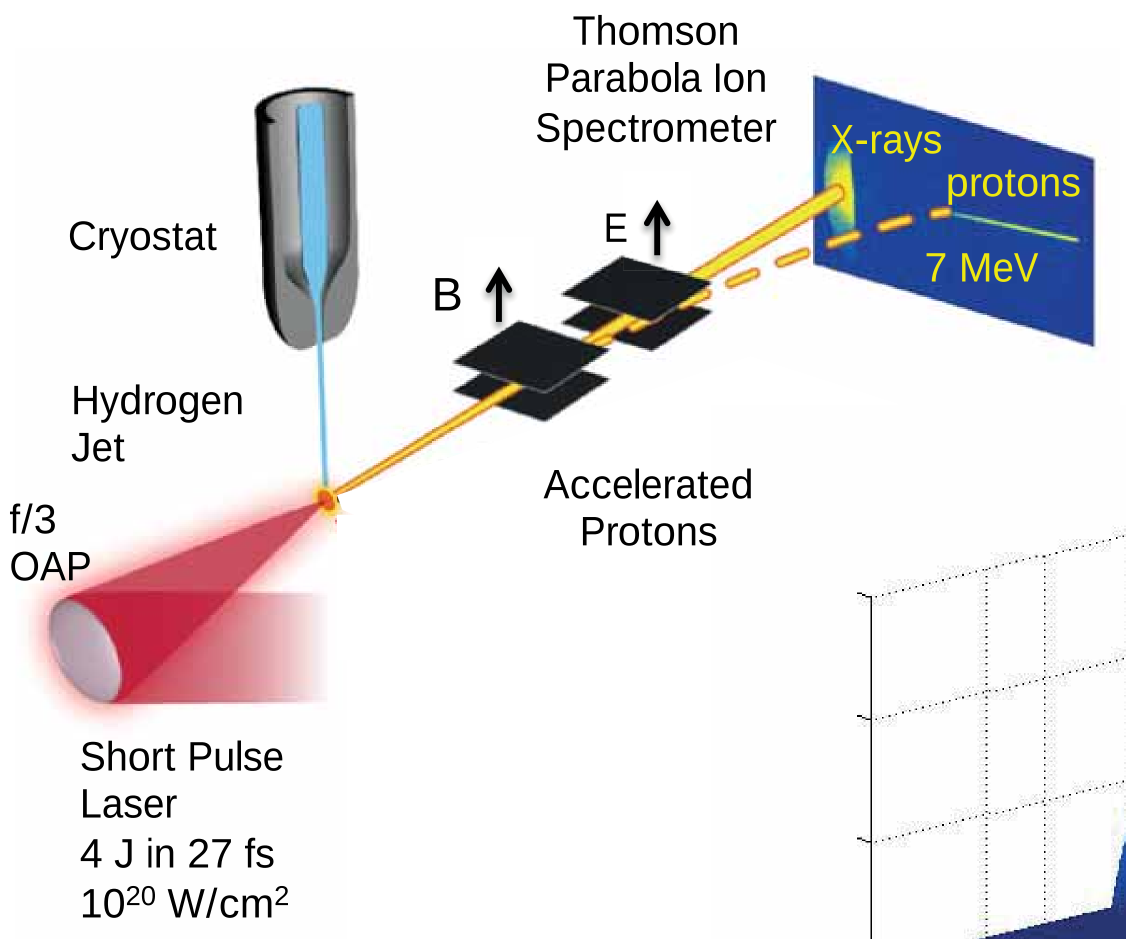
Target Normal Sheath Acceleration
(TNSA)

Experiment at HZDR: Proton acceleration using a solid-density hydrogen jet



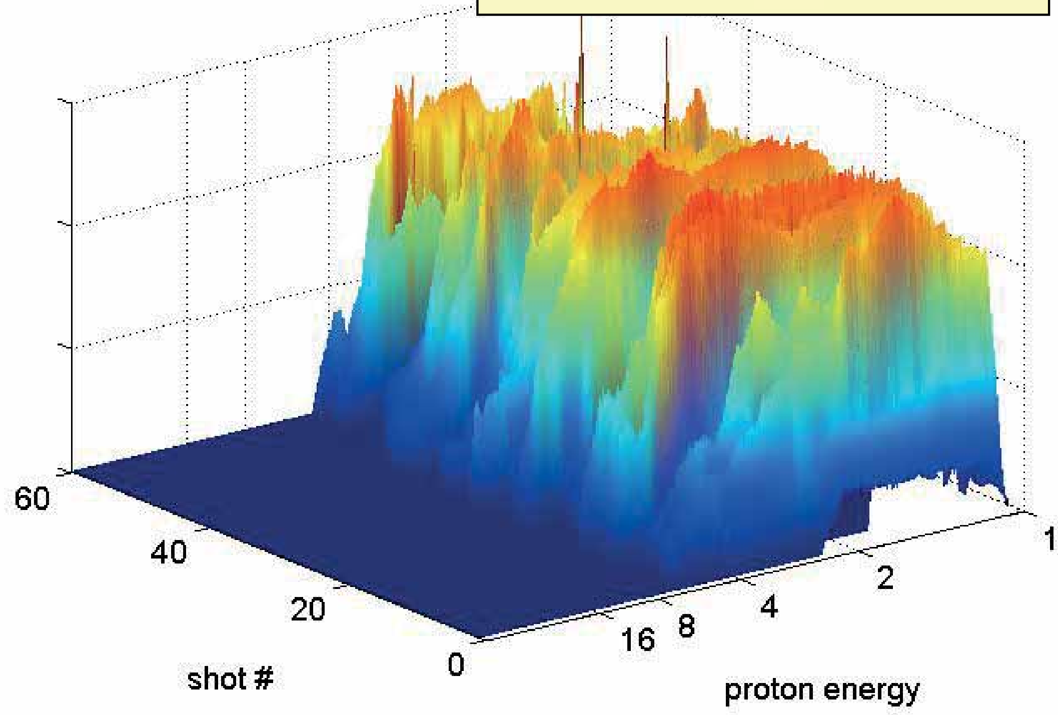


Experiment at HZDR: Proton acceleration using a solid-density hydrogen jet



pure proton spectrum ✔

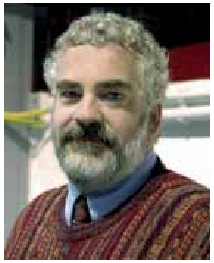
proton acceleration with 1 Hz ✔



Quick summary of laser proton acceleration

- Solid density hydrogen jet as a target for laser proton acceleration ✔
- Pure proton beams accelerated by TNSA ✔
- ~10 MeV protons with 1 Hz ✔

<0.002 mm mrad which is at least 100 times smaller than the emittance of thermal ion sources
[T. Cowan et al. Phys. Rev. Lett. 92, 204801 (2004)]



T. Cowan

S. Glenzer

- Emittance is compelling for a novel injector scheme ✔

TNSA spectrum is not useful for most applications, monoenergetic spectrum and higher proton energies required ✖

Motivation – Collisionless Shock Acceleration for Monoenergetic Proton Acceleration

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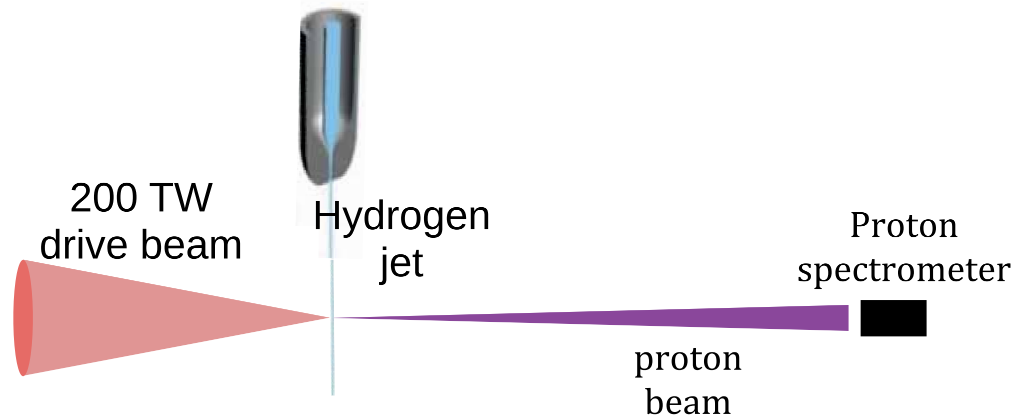
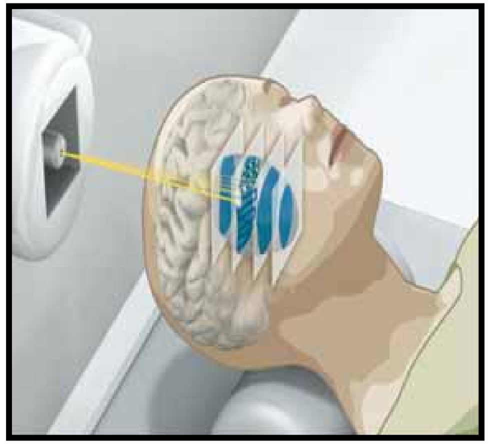
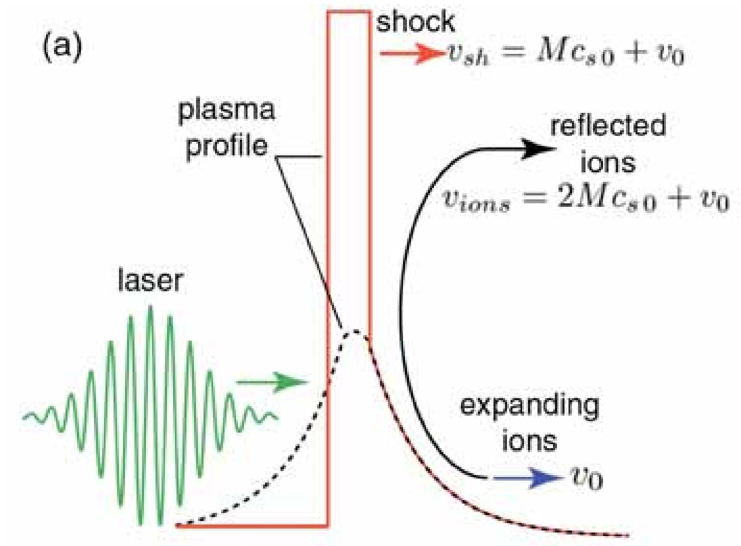
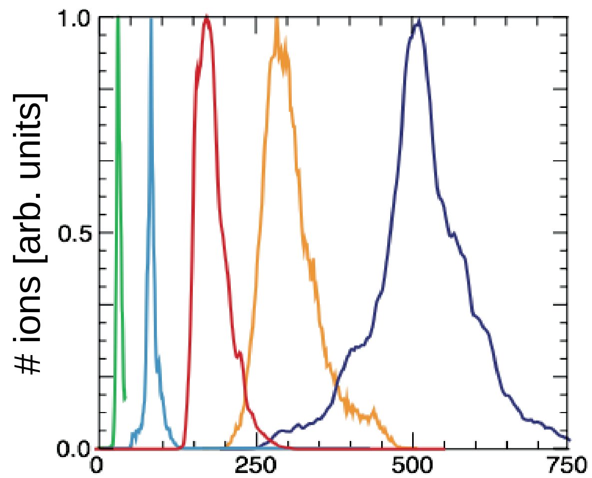
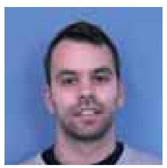






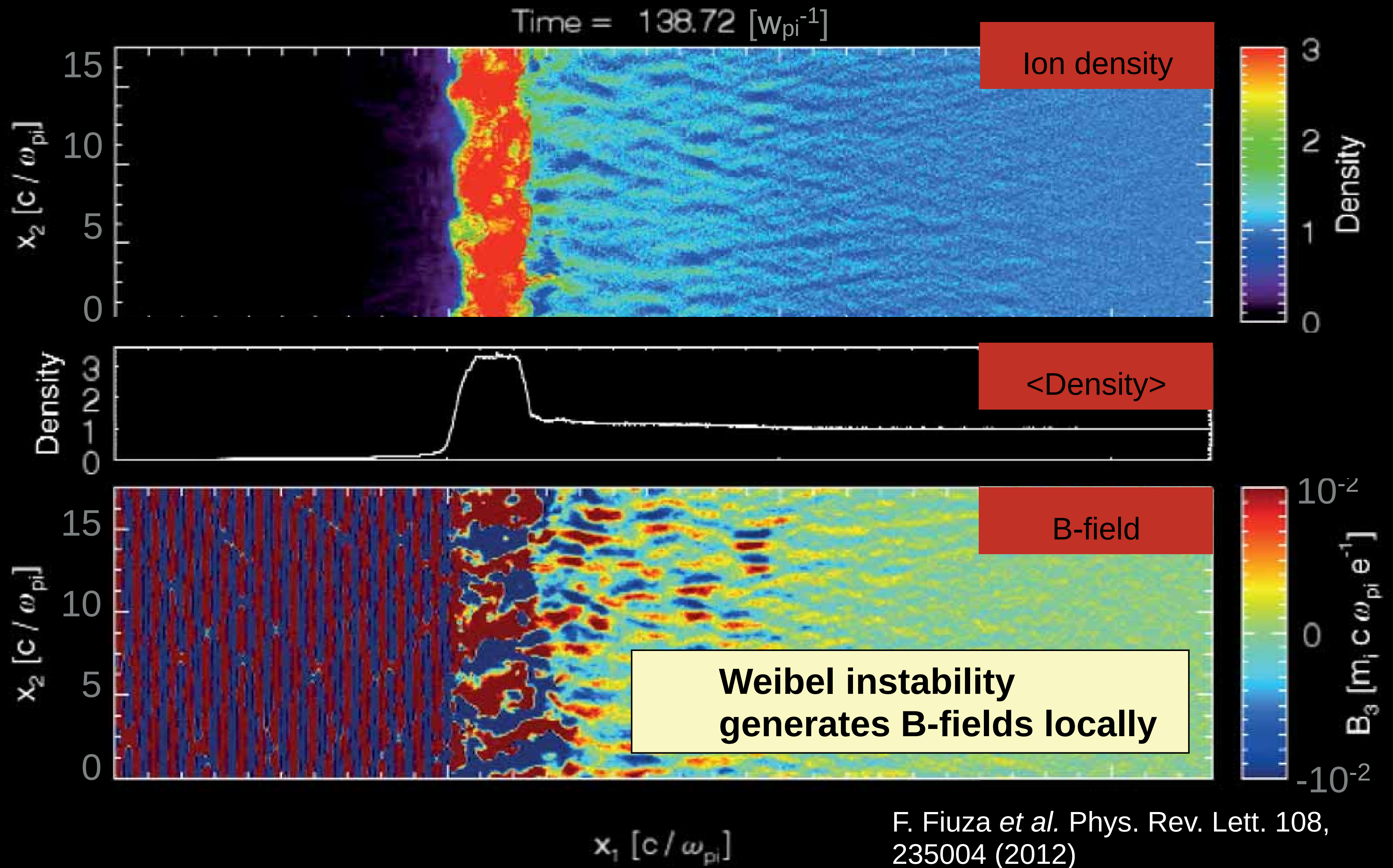
Collisionless Shock Acceleration may lead to better energy scaling





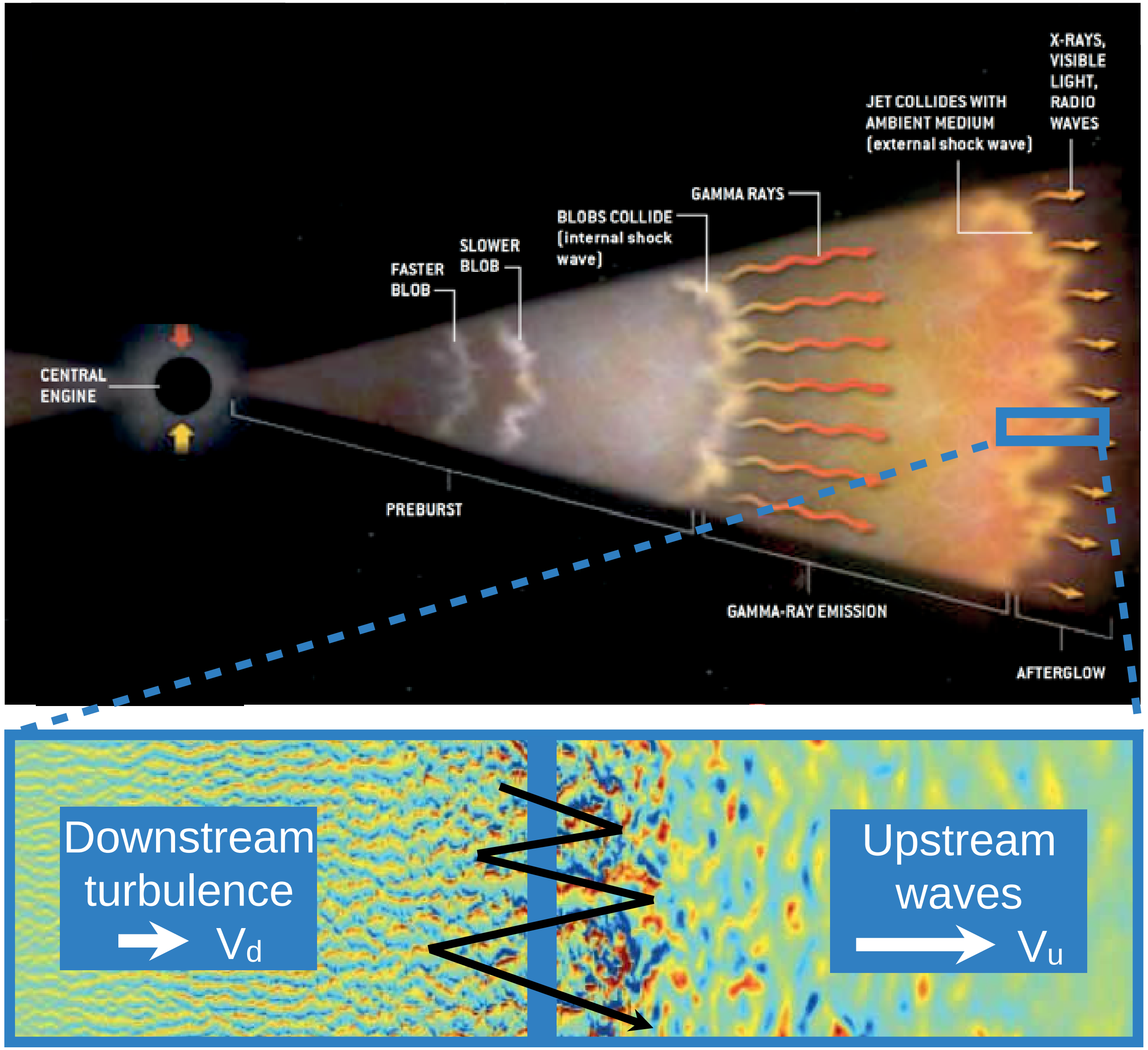
F. Fiuza et al. Phys. Rev. Lett. 109, 215001 (2012)
F. Fiuza et al. Phys. Rev. Lett. 108, 235004 (2012)

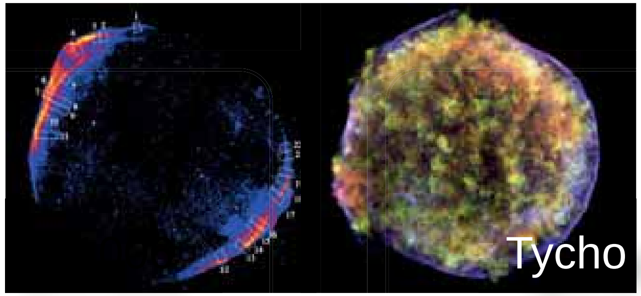
Collisionless Shock Acceleration and the role of the Weibel instability

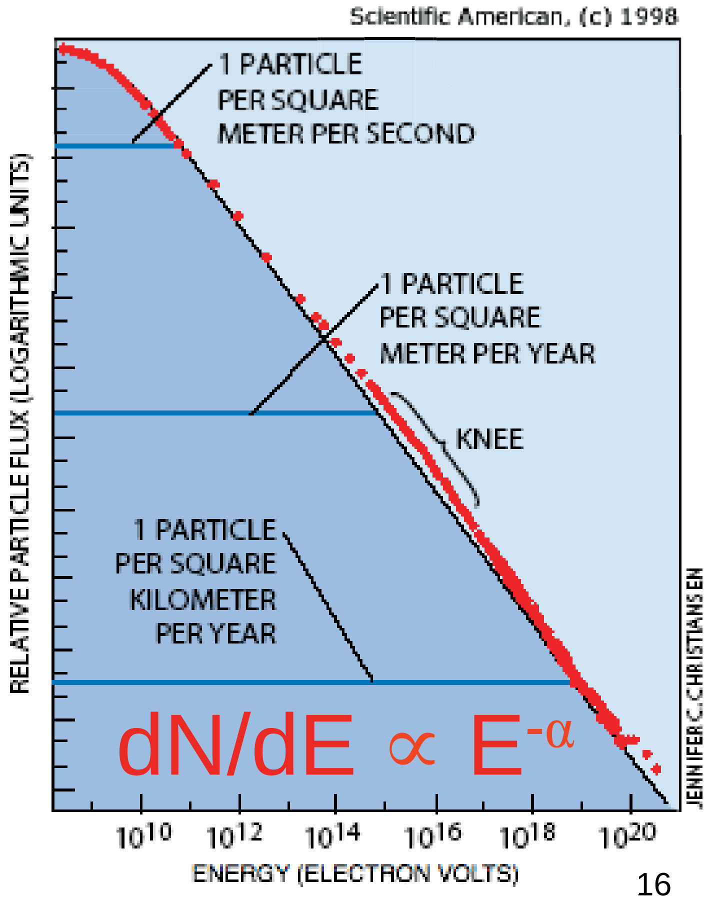


F. Fiuza *et al.* Phys. Rev. Lett. 108, 235004 (2012)

Motivation – Collisionless Shock Acceleration and Laboratory Astroparticle Physics

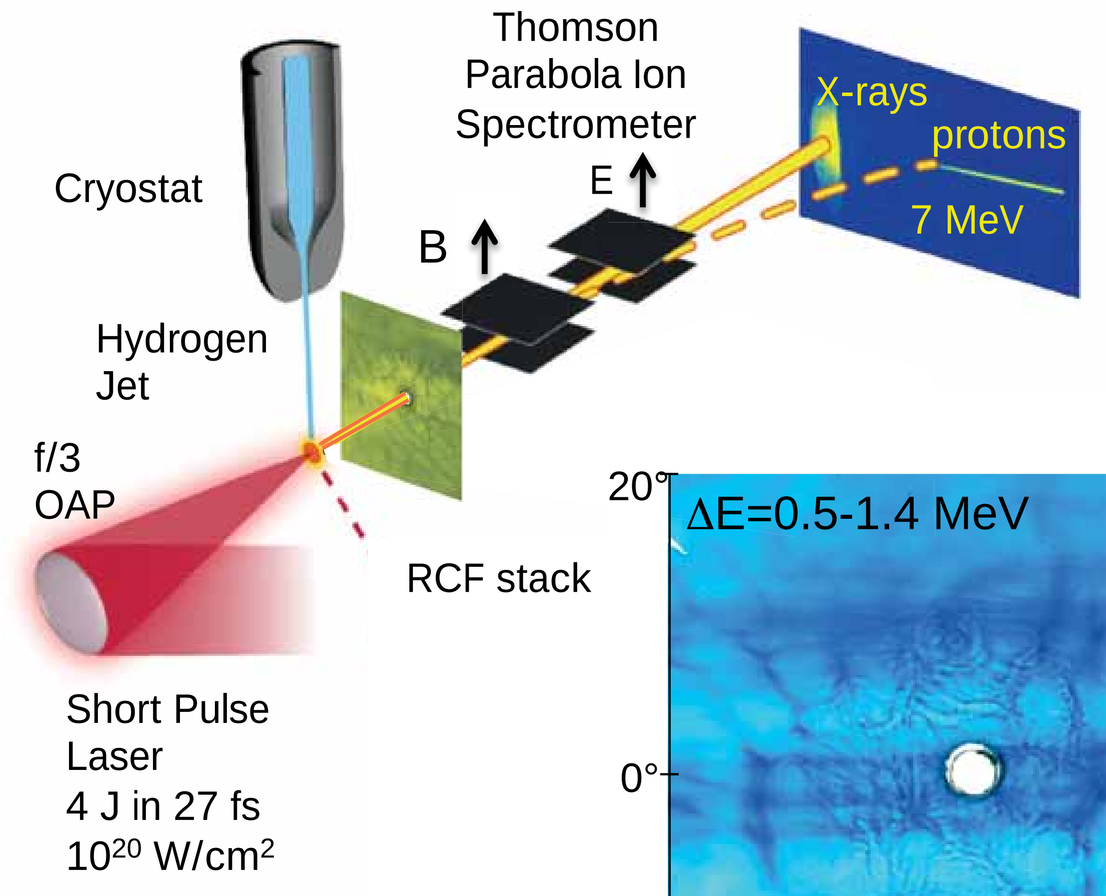


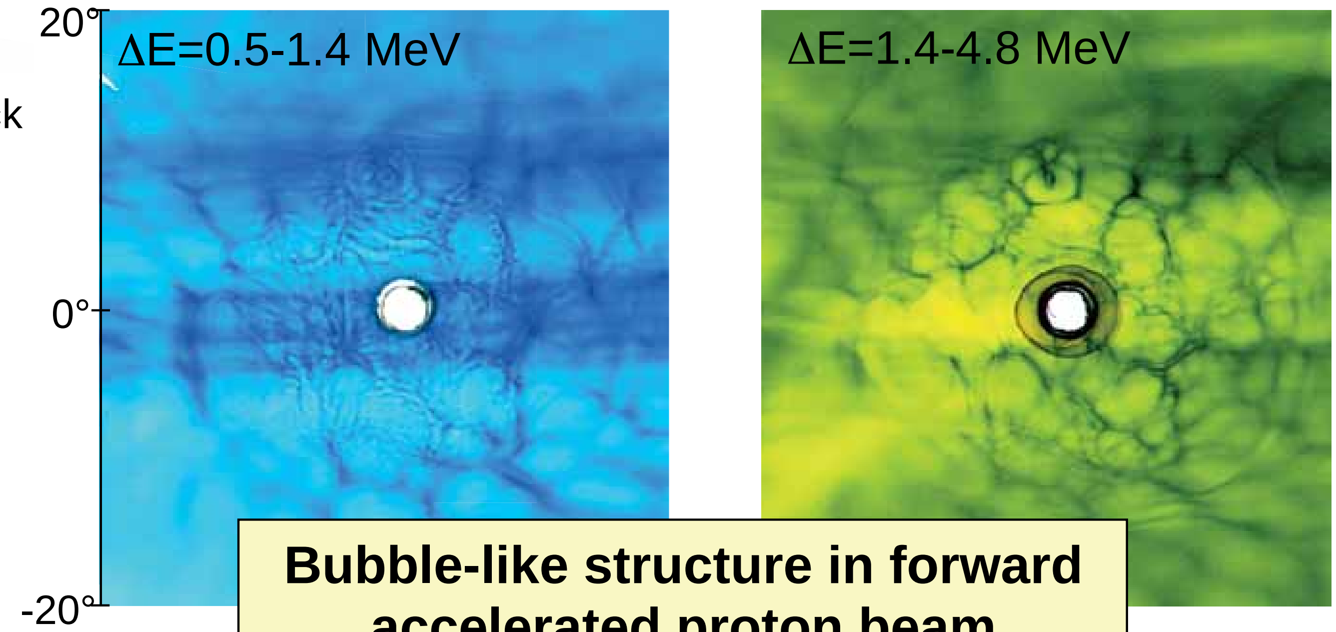




N. Gehrels, L. Piro, and P.J.T. Leonard, Scientific American (2002)
R. Blandford & D. Eichler, Physics Reports 154, 1 (1987)

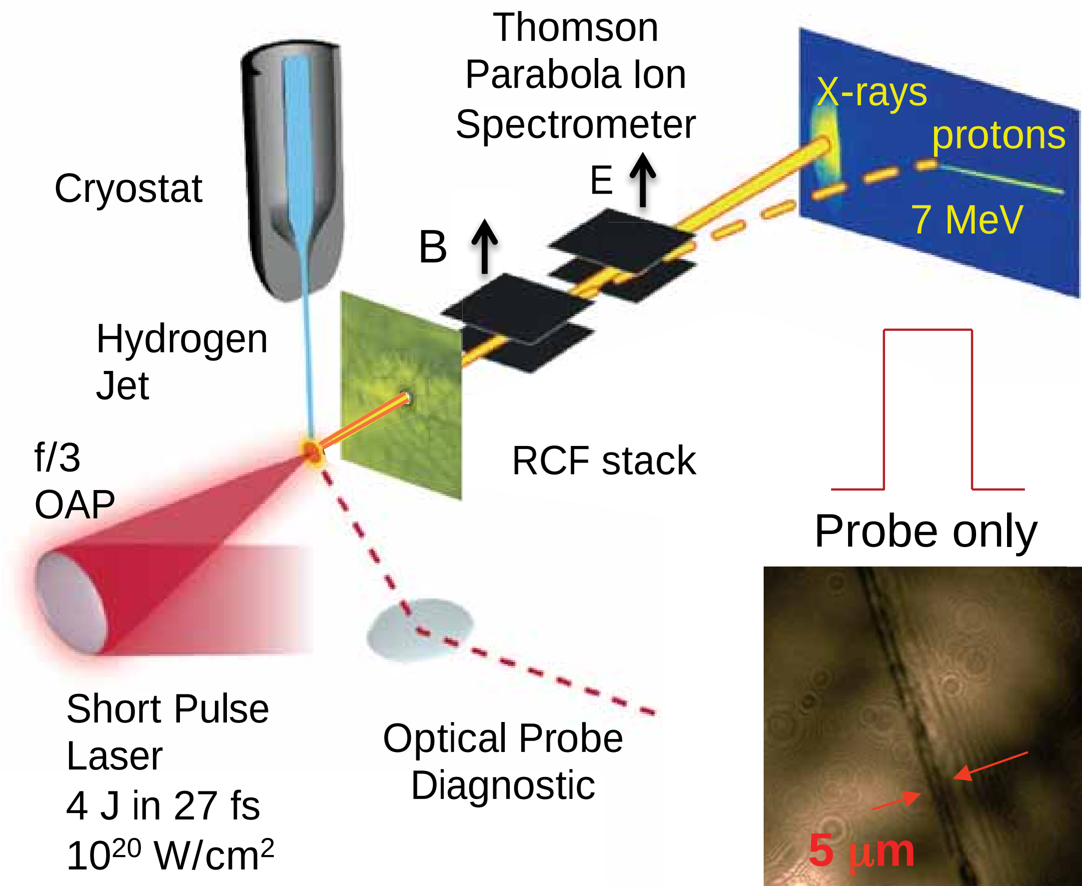
Radiochromic film shows bubble-like structure in forward-accelerated beam

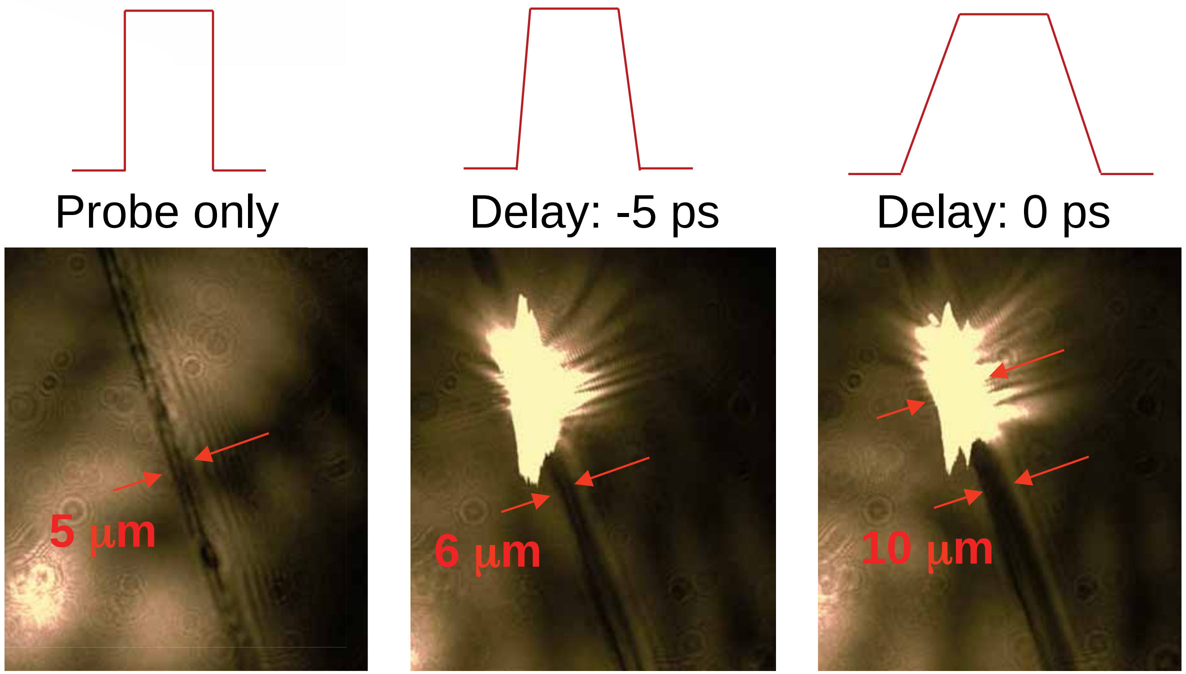




Bubble-like structure in forward accelerated proton beam

Optical probe provides estimate of the length of the plasma density gradient





Length of plasma density gradient: L_p=5 μm

2D PIC simulation using experimental parameters reveals Weibel instability

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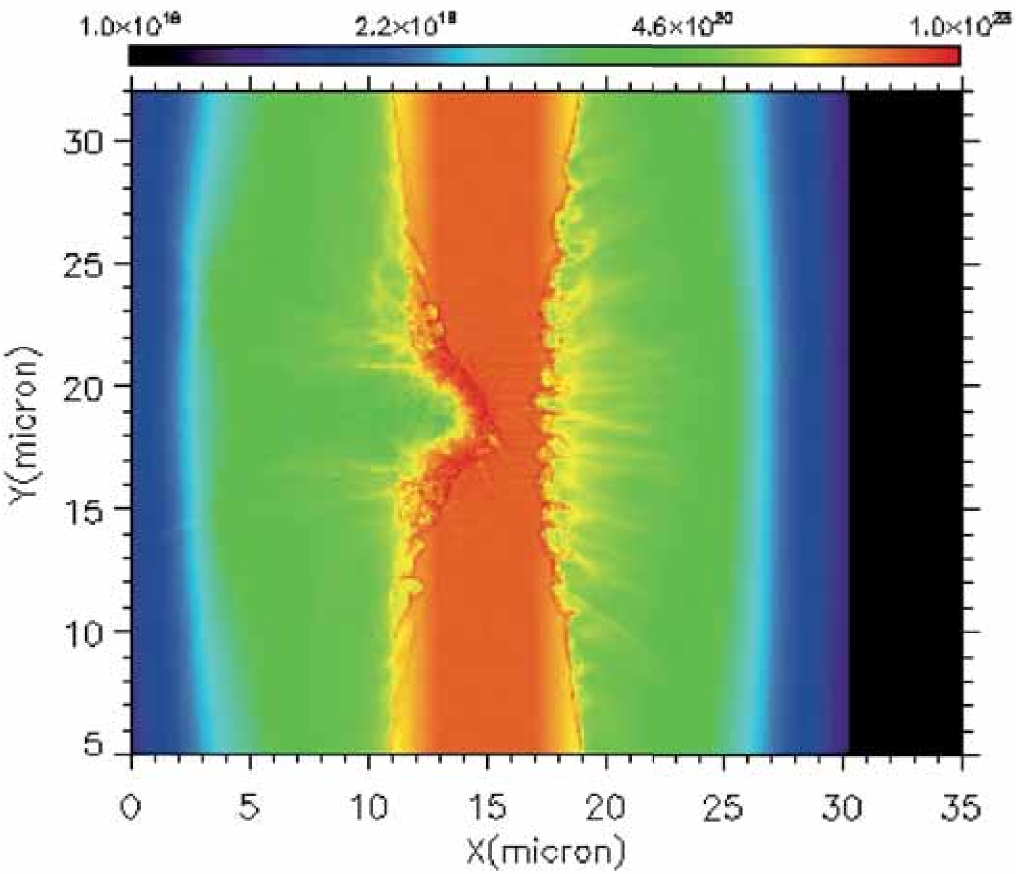
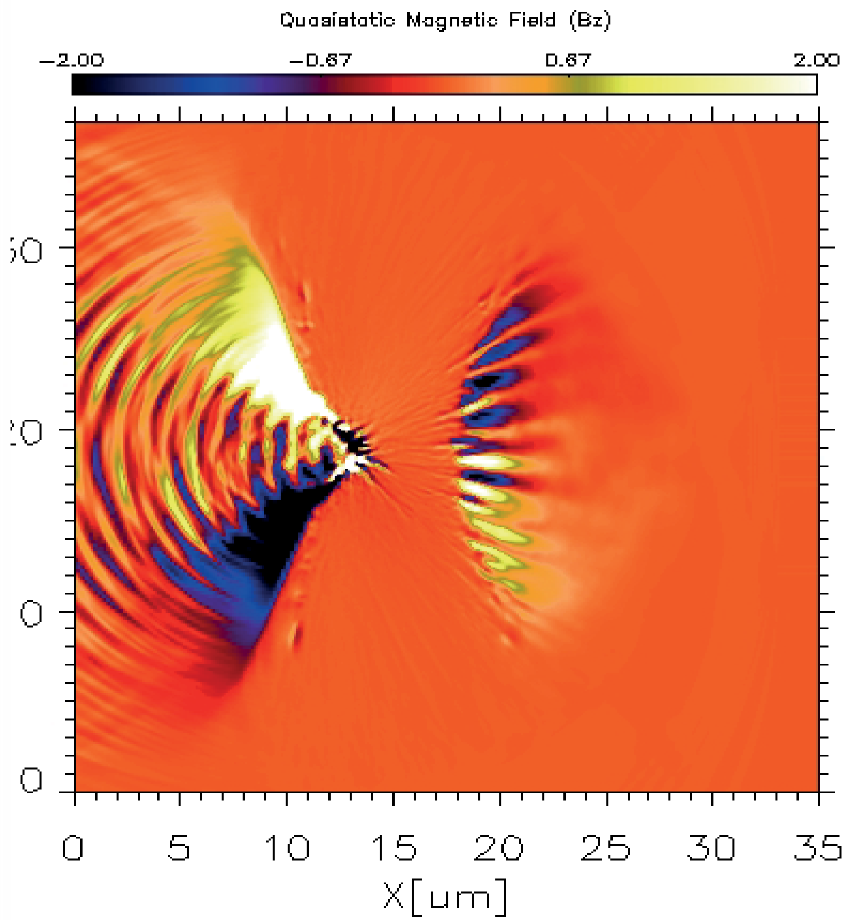
proton density





Modulation of the proton density in the rear side density gradient

Modulation in the B-field might be due to the Weibel instability

2D PIC simulation using experimental parameters reveals Weibel instability

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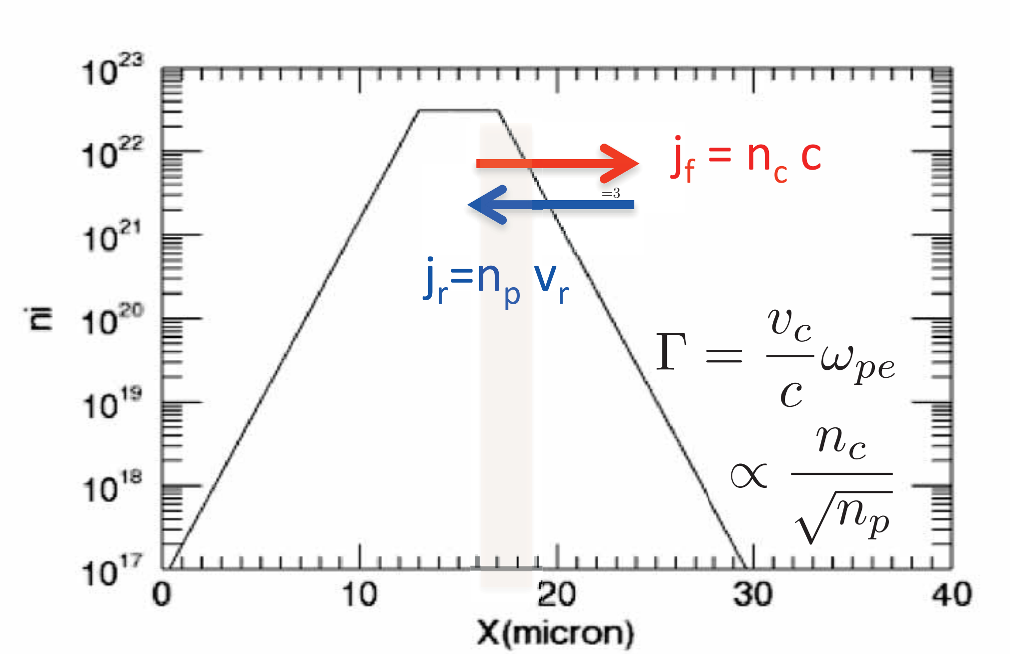
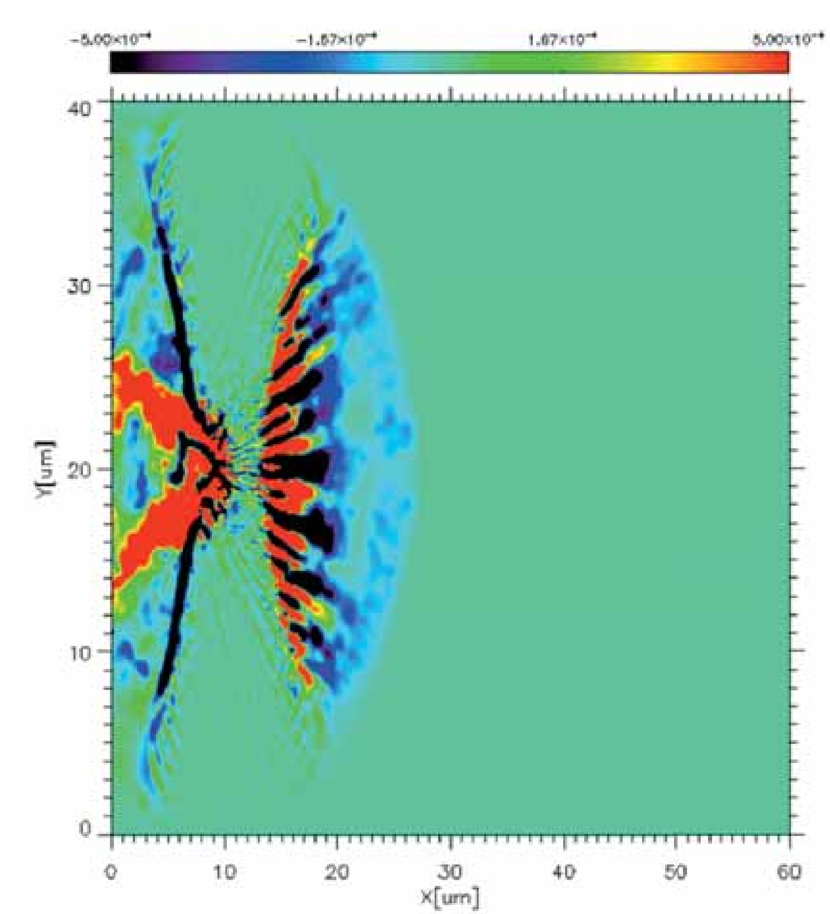


C. Ruyer et al.
Physics of Plasmas 22, 082107 (2015)

Current density at early times (100 fs)



Counter streaming currents go Weibel unstable

Weibel filament size is local plasma wavelength

2D PIC simulation using experimental parameters reveals Weibel instability

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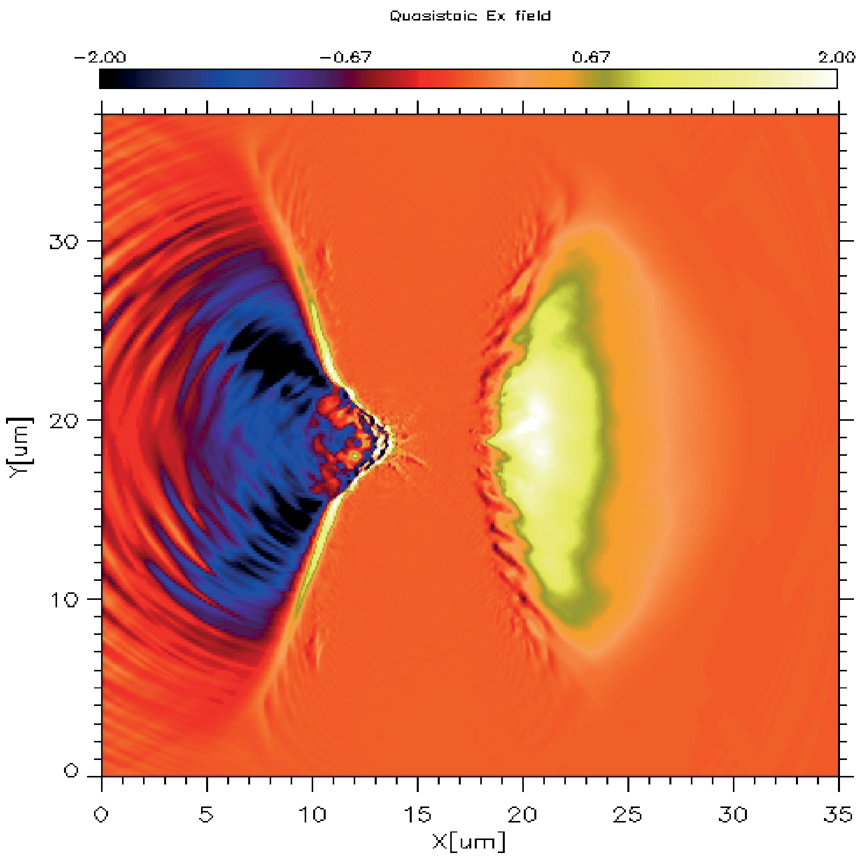
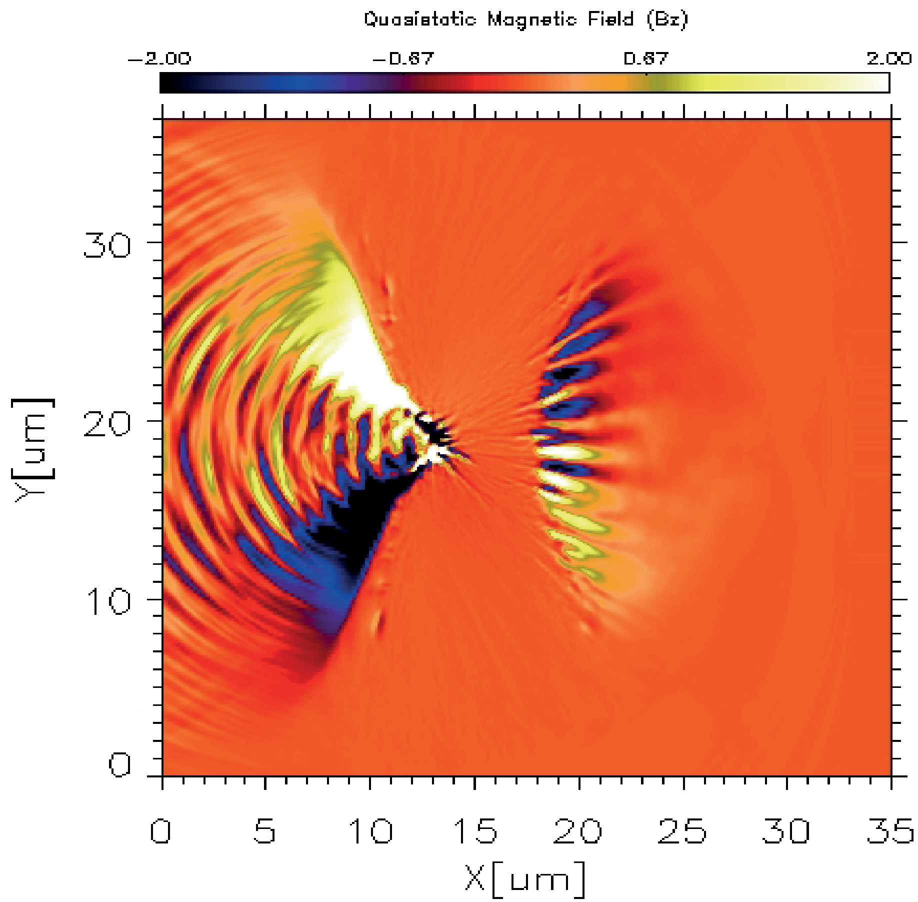
E_x-field

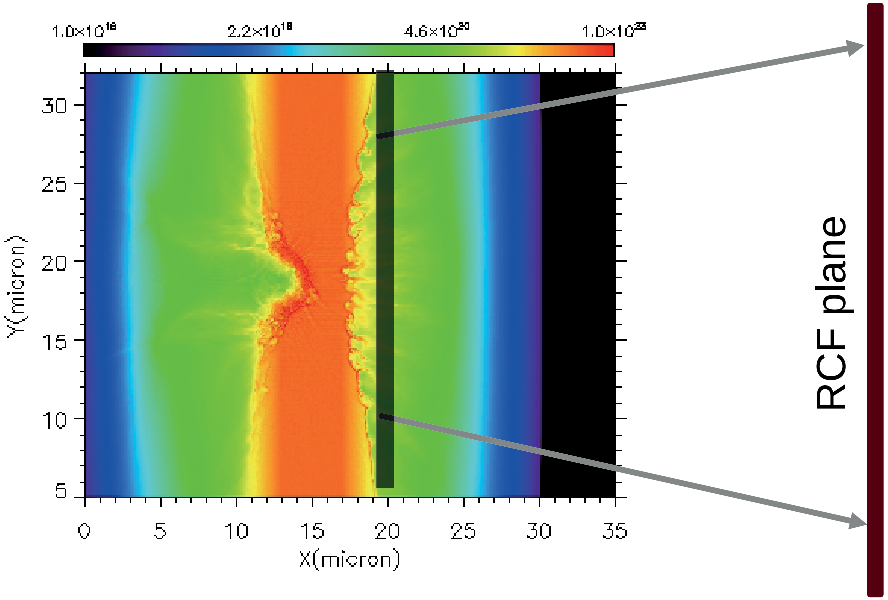


B_z field

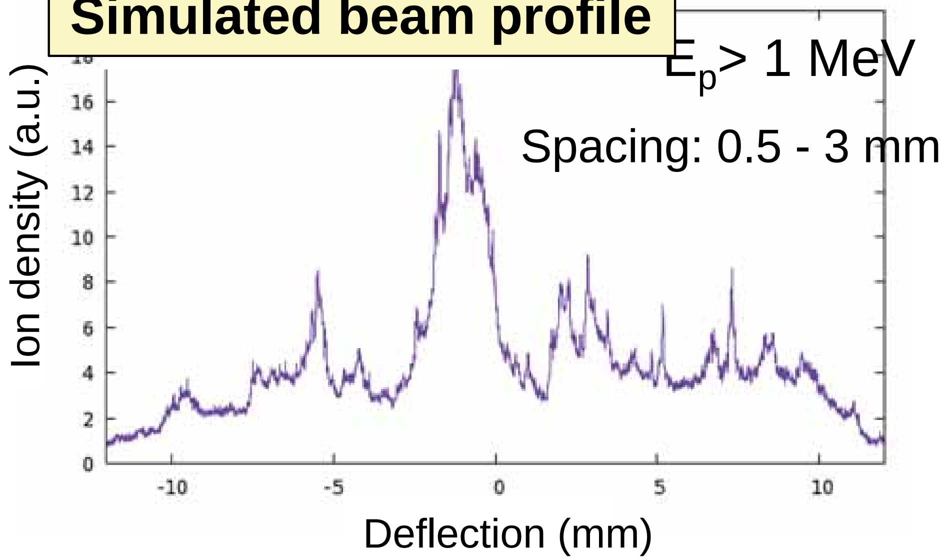


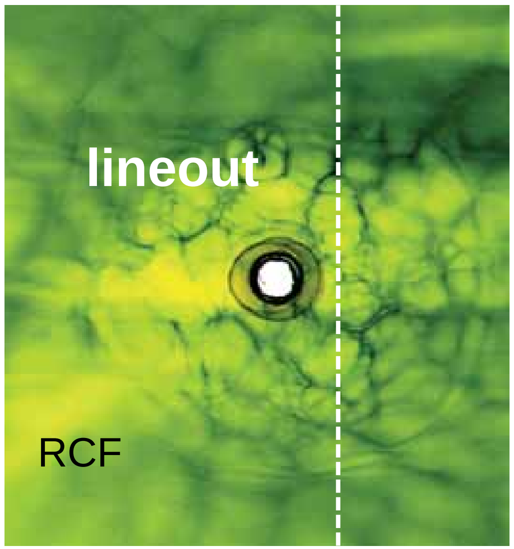
TNSA accelerated protons pass the Weibel B-fields

Agreement between simulations and experimental results

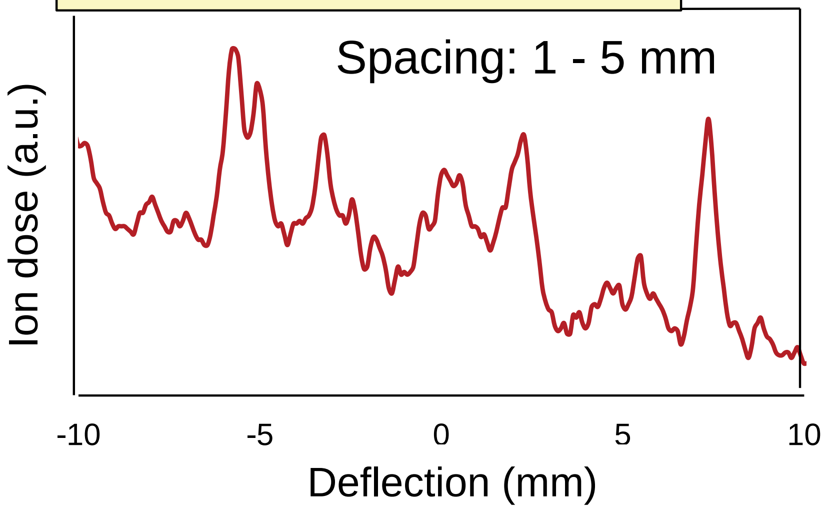


Simulated beam profile



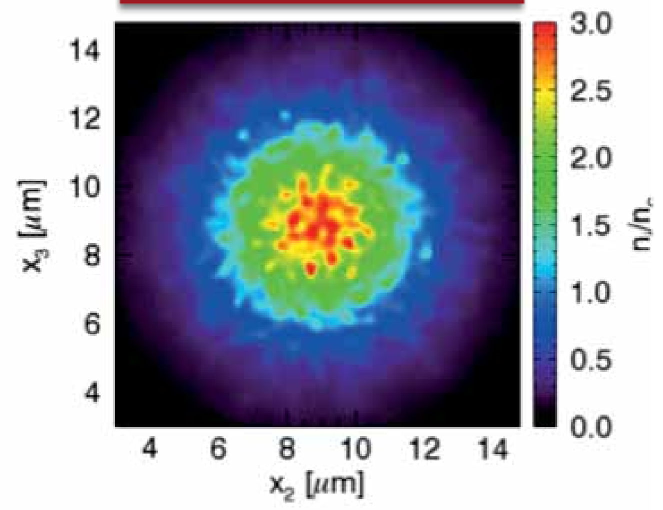


Measured beam profile

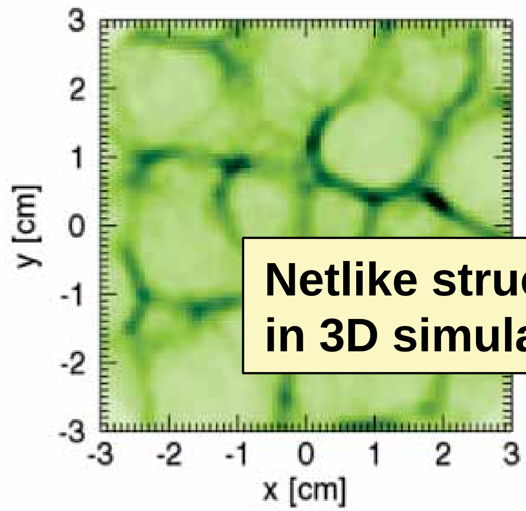


3D PIC simulations reproduce experimental results

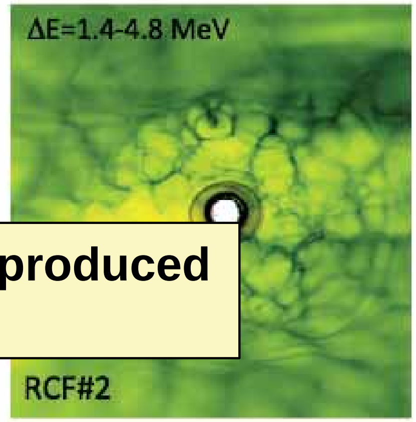
Ion density (transverse profile)



Projection of accelerated ions in simulated detector

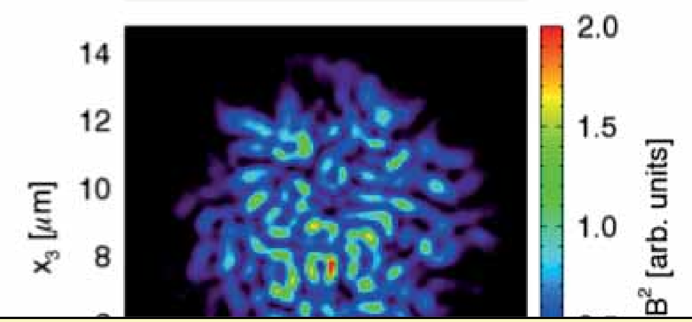


Experimental results from RCF detector

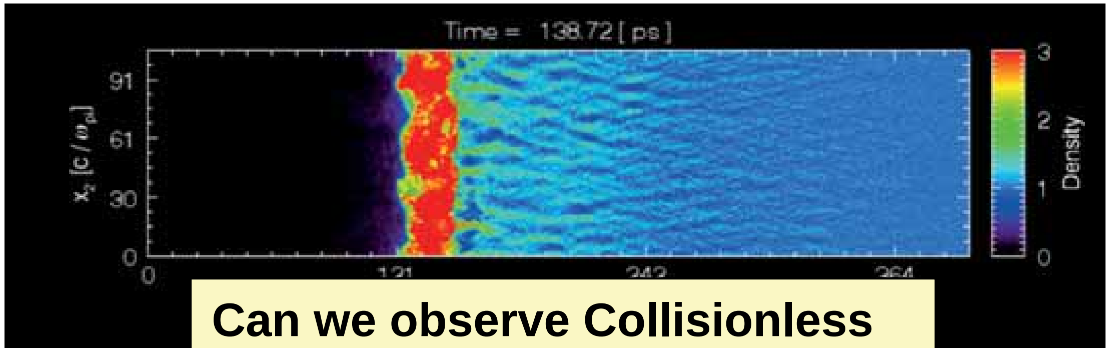


Netlike structure is reproduced in 3D simulations

Magnetic energy (transverse profile)



Caustic formation requires B fields from Weibel instability of the order of 100 MG ✔



Can we observe Collisionless Shock Acceleration ?

Experiment at Titan laser at LLNL

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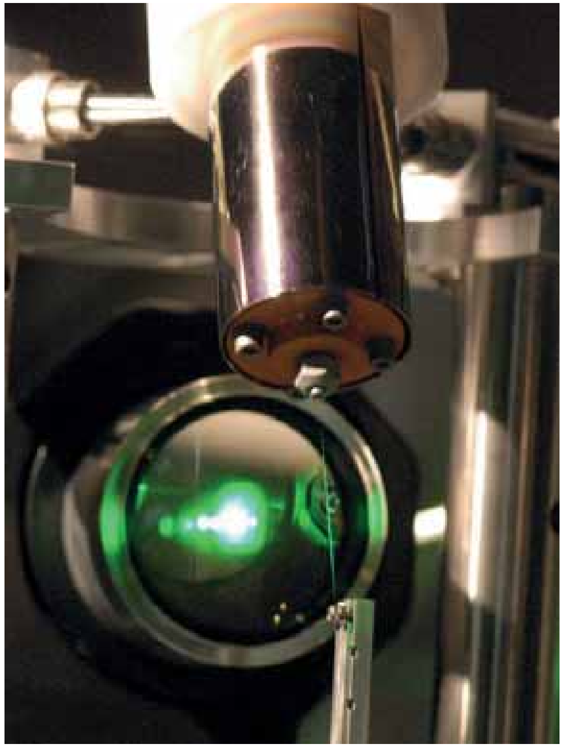
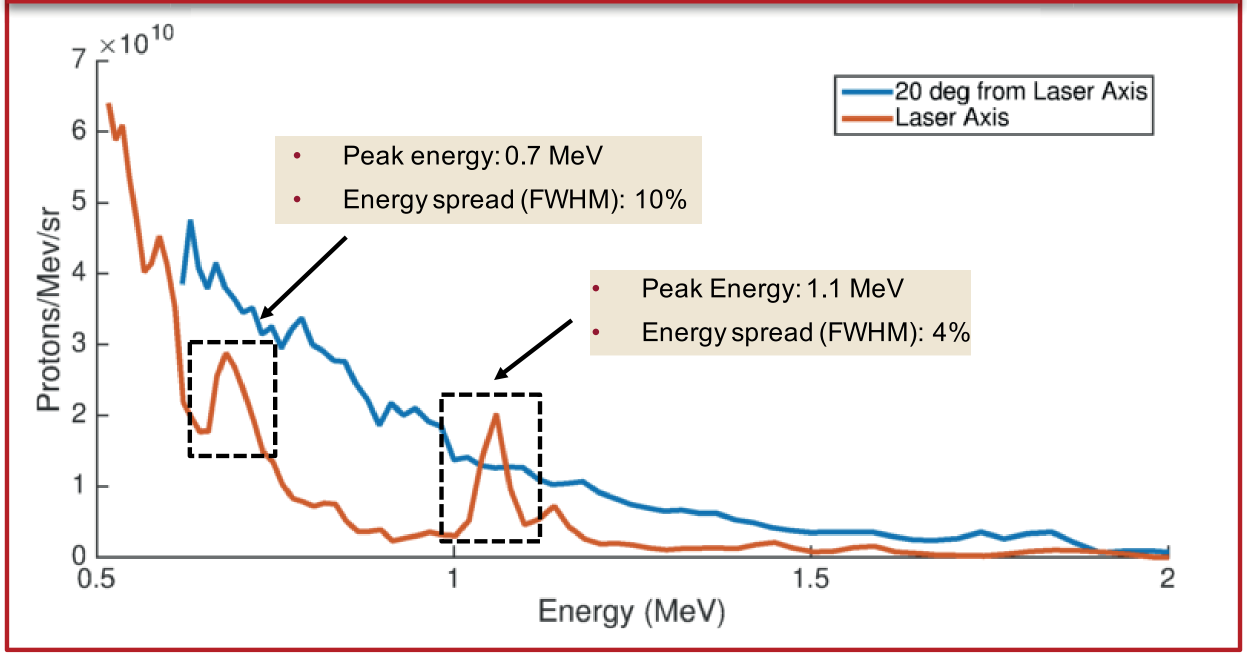


Proton Spectrum from 10μm H_2 Jet at 5×10^{19} W/cm2



Lawrence Livermore National Laboratory

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- Monoenergetic features in laser-forward direction that cannot be explained by TNSA
- Radiation pressure driven shock velocity matches 1 MeV peak

Quasi-monoenergetic features in the proton spectrum appear to be from Collisionless Shockwave Acceleration

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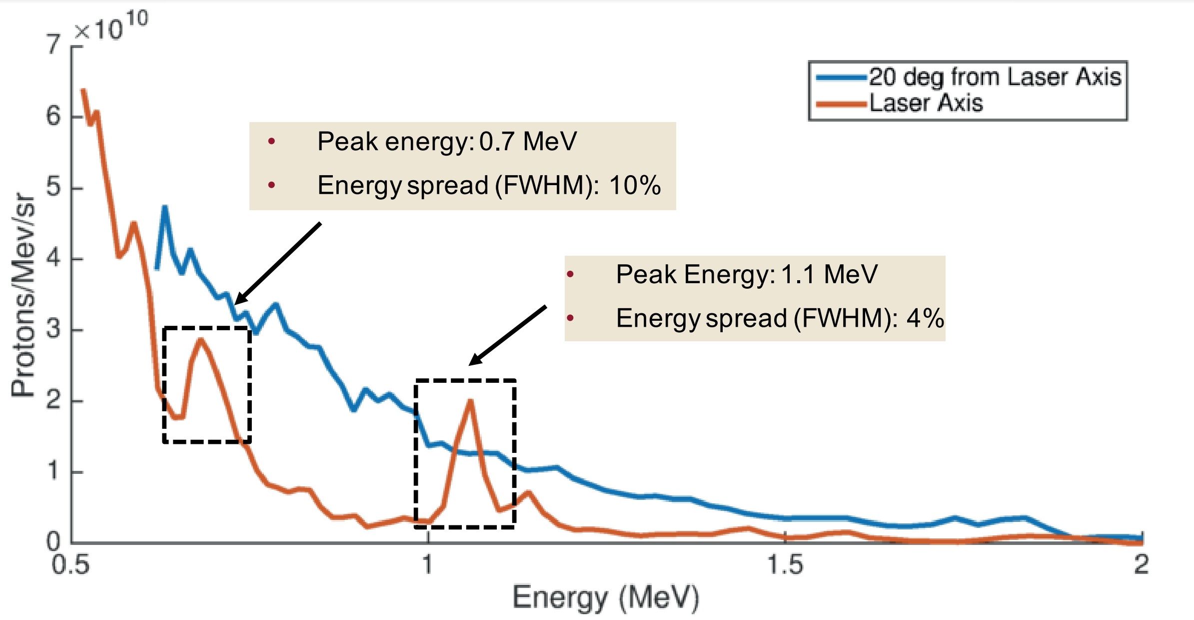
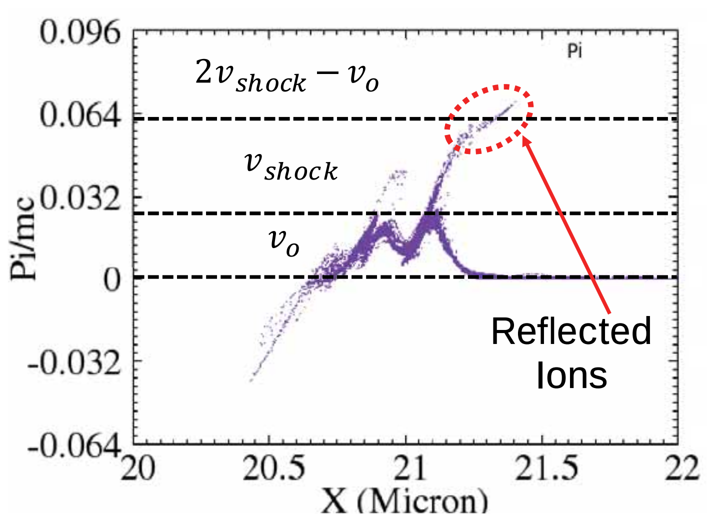
Proton Spectrum from 10μm H_2 Jet at $5x10^{19}$ W/cm2



Proton Phase Space from 2D PIC Simulation



- Shock front reflects ions, producing a quasi-monoenergetic MeV peak
- A second peak appears to due to the accumulation of protons along the shock front

Onset of Collisionless Shock Acceleration might be observed in addition to Weibel radiograph

Summary

Laser particle acceleration for medical applications

- proton acceleration up to 10 MeV by TNSA from cryogenic solid-density hydrogen plasma
- laser-driven proton accelerator with 1 Hz

Laboratory astroparticle physics

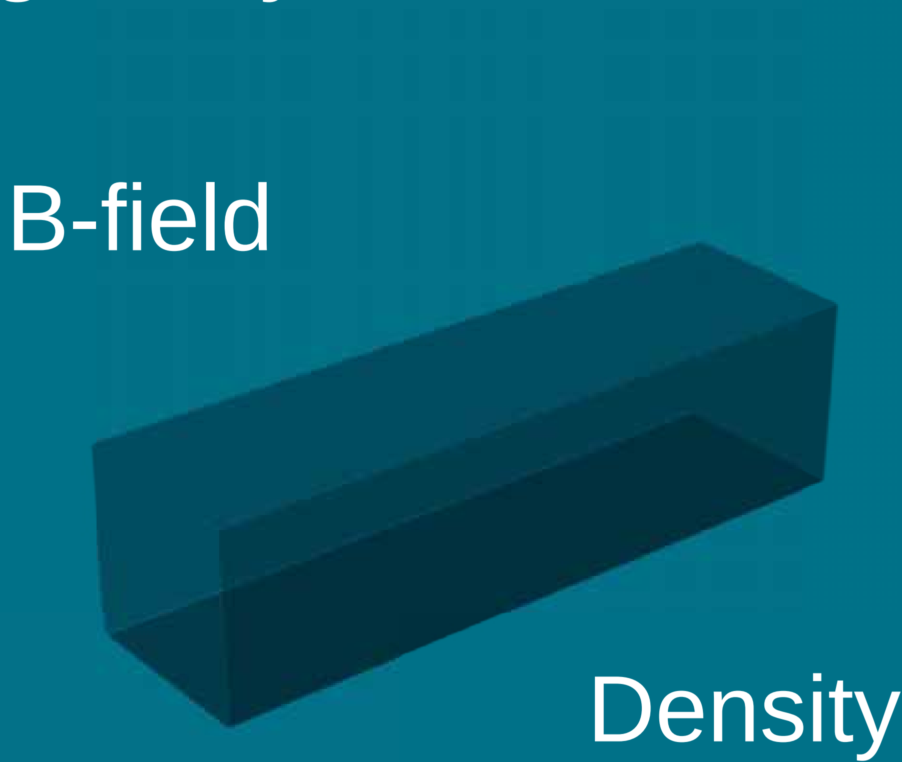
- proton radiography of magnetic fields due to Weibel instability
- quasi-monoenergetic spectral features may reveal onset of Weibel-mediated Collisionless Shock Acceleration
- experimental platform for studies of magnetic field amplification and Collisionless Shock Acceleration using femtosecond high intensity lasers

Outlook:
Observation of collisionless shock acceleration and Weibel instabilities using x-ray free-electron lasers

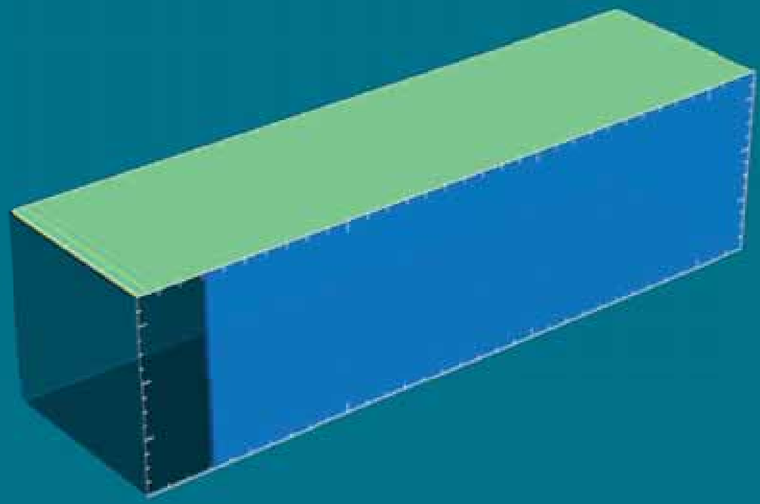
Observation of Weibel instabilities using x-ray free-electron lasers

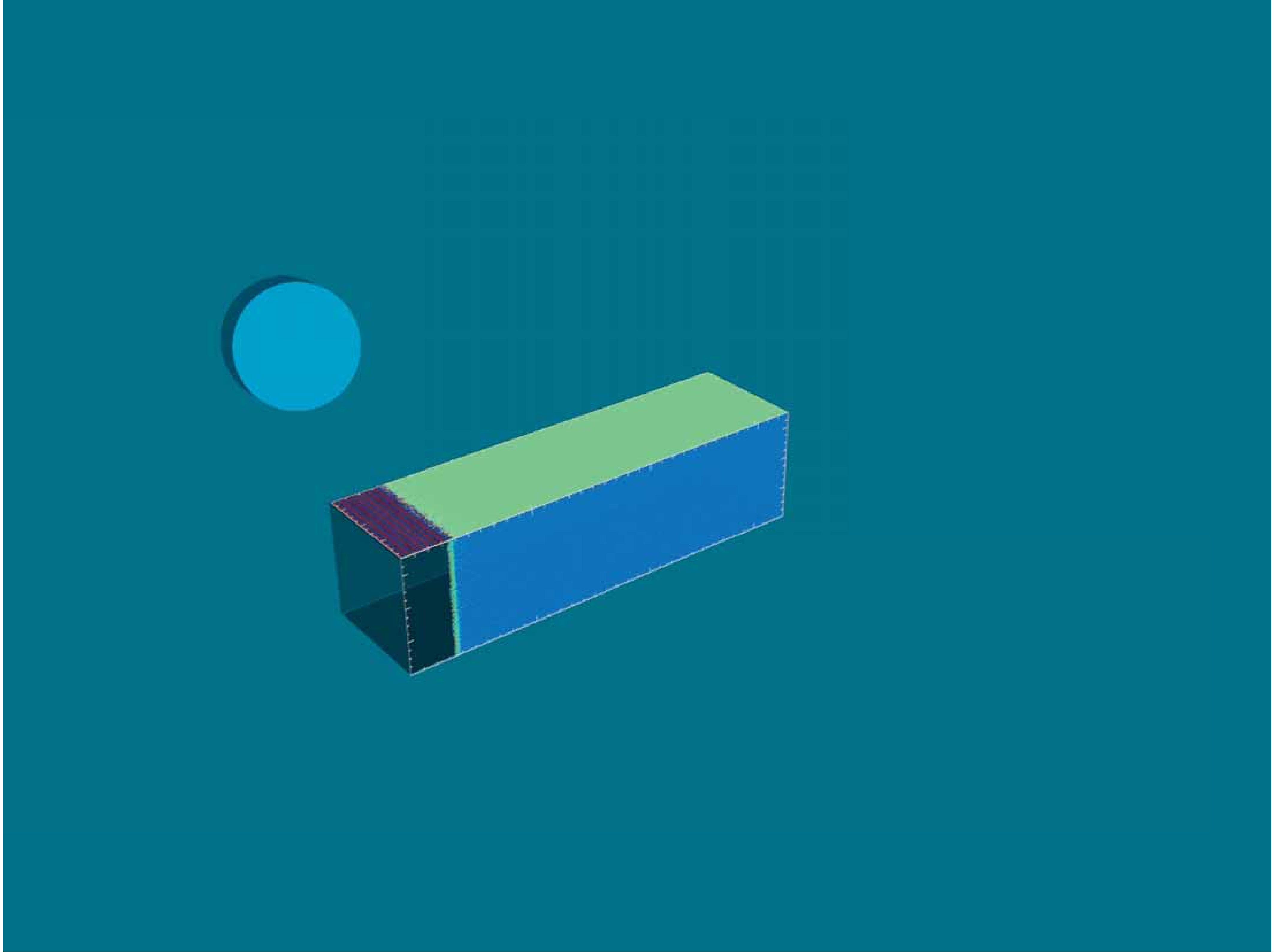
Laser target

Observation of Weibel instabilities using x-ray free-electron lasers

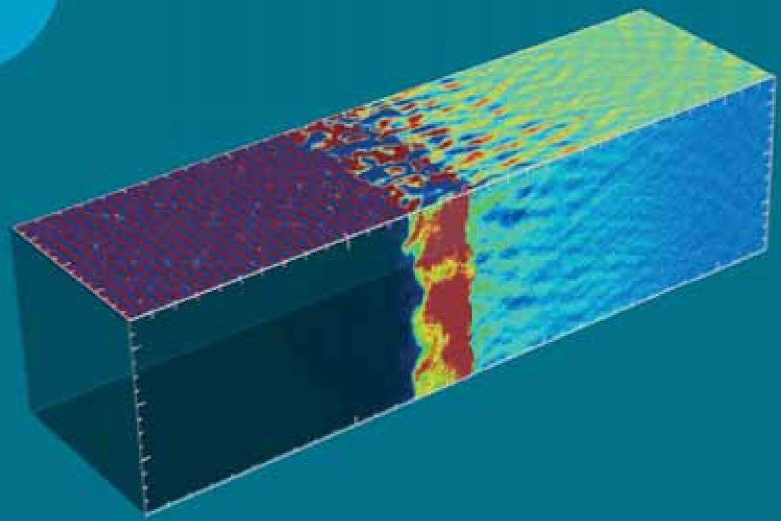


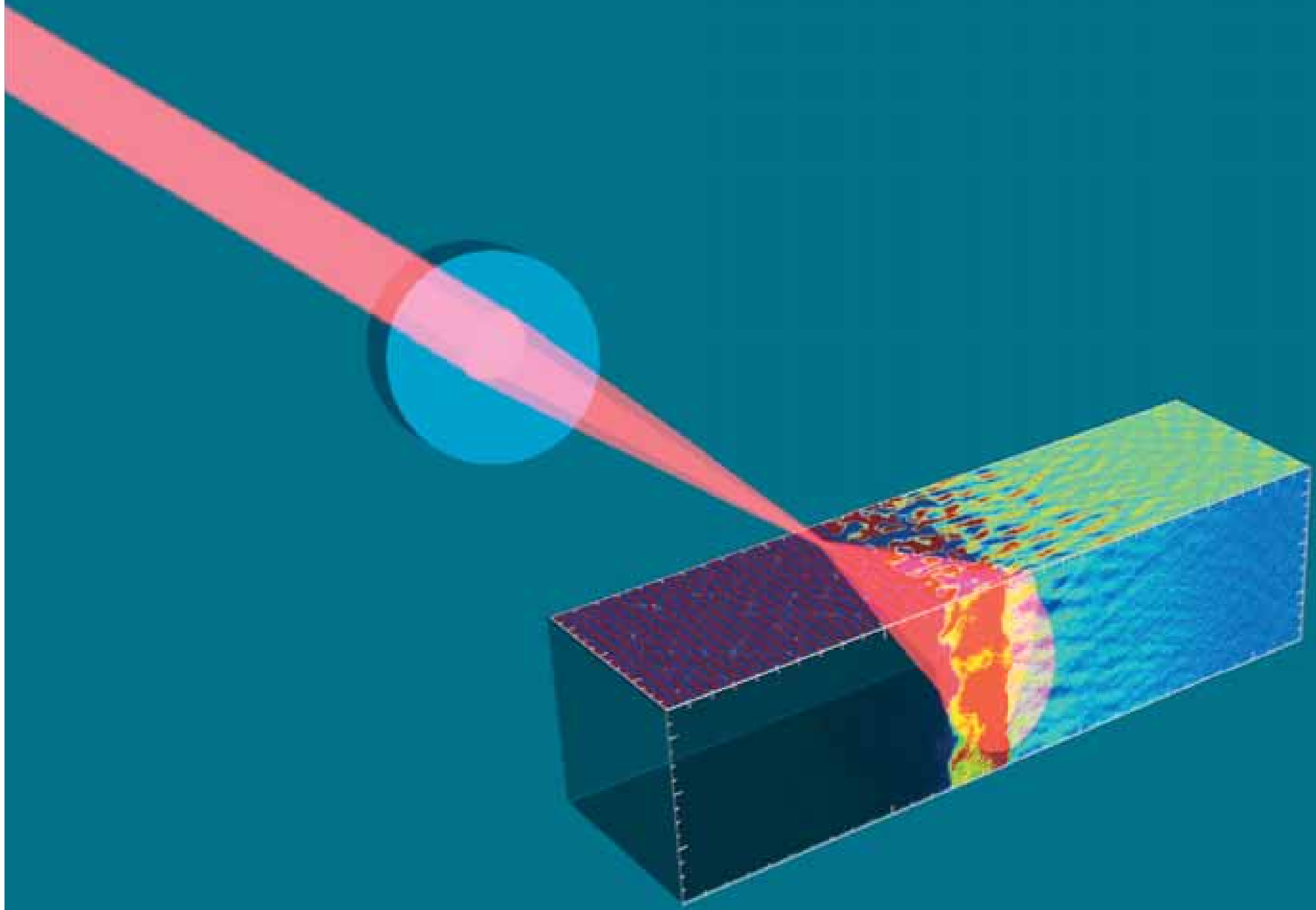
Observation of Weibel instabilities using x-ray free-electron lasers



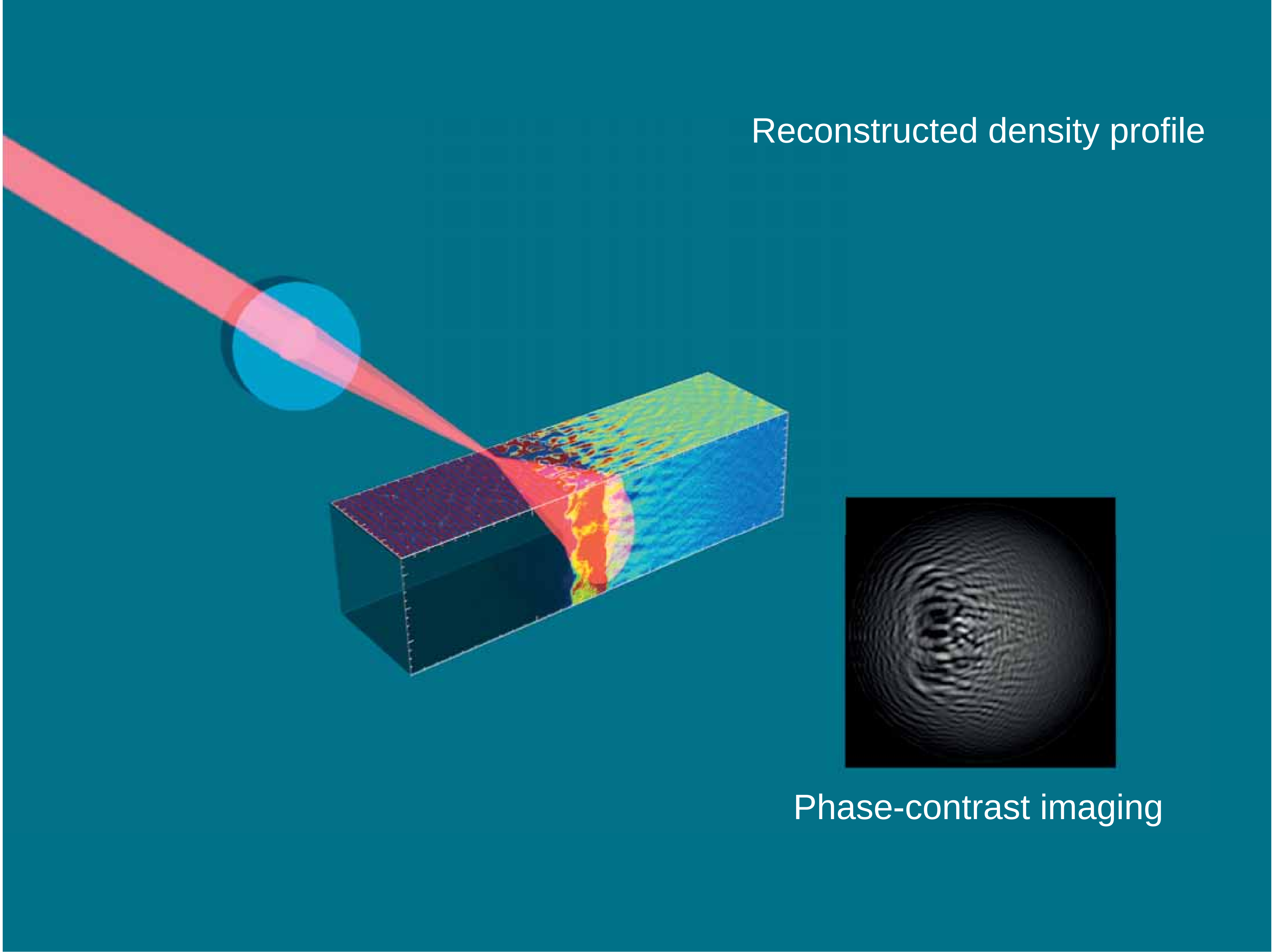


X-ray laser

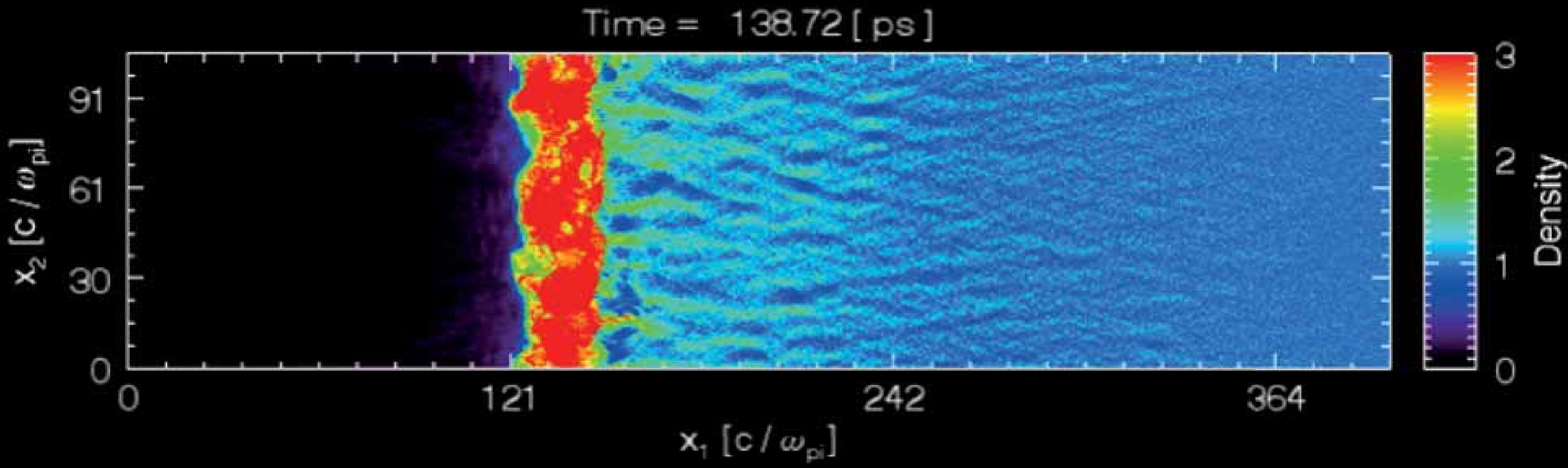




Phase-contrast imaging


Reconstructed density profile
Phase-contrast imaging

Cryogenic hydrogen jets and high power lasers provide new opportunities to investigate magnetic field amplification and Collision Shock Acceleration in the laboratory



Thank you for your attention!