Physics Opportunities in High-Energy-Density-Physics

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Summary

We have entered a "golden age" of high-energy-density-physics (HEDP) using a high-energy laser system

- The Omega Laser and National Ignition Facilities allow for a wide range of HEDP experiments for programmatic needs and fundamental science
  - laboratory astrophysics, including the possibility of explaining the source of galactic magnetic fields
  - planetary science: earth-like, gas giants, extrasolar
- HEDP opportunities would be greatly enhanced with a laser system with a peak intensity of $\sim 10^{24}$ W/cm^2
  - especially coupled to a high-energy laser system
- Two beams of OMEGA EP could be used to pump an optical parametric chirped-pulse beamline (EP OPAL)
  - 1.6 kJ in 20 fs; an unprecedented intensity of $\sim 10^{24}$ W/cm^2

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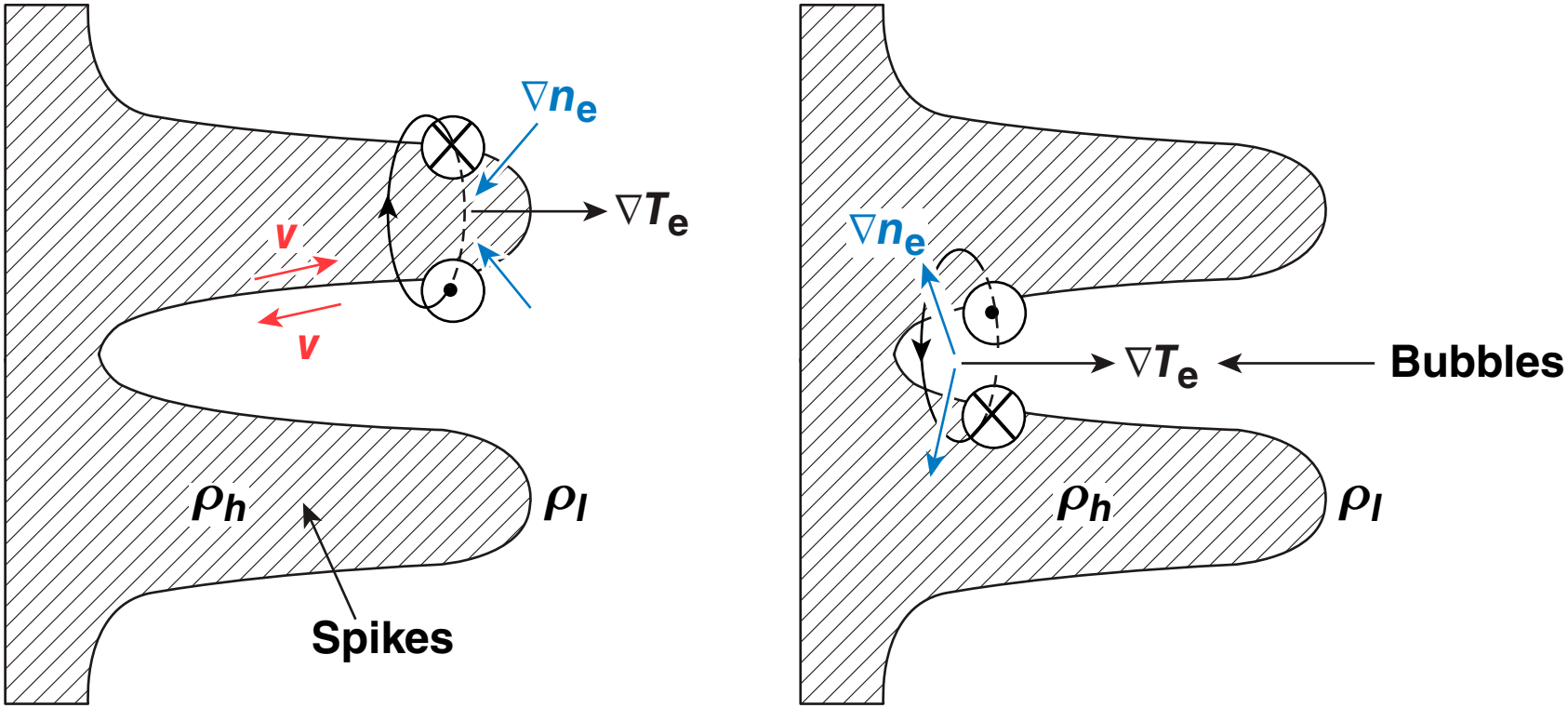
The Rayleigh–Taylor (RT) instability in laser-driven targets generates large amounts of fluid vorticity*

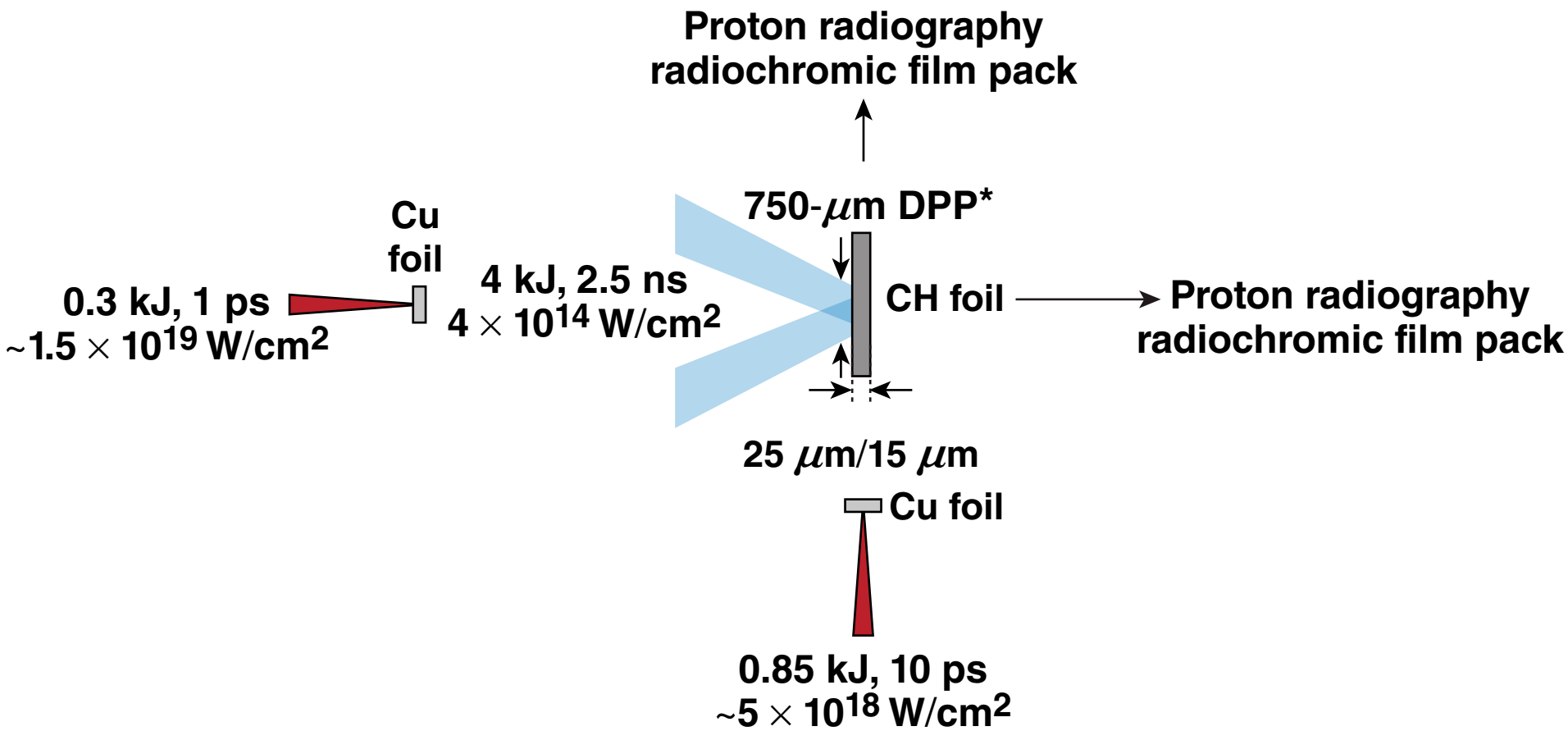


Azimuthal magnetic fields are generated by $\nabla n_e \times \nabla T_e$.

*K. Mima, T. Tajima, and J. N. Leboeuf, Phys. Rev. Lett. 41, 1715 (1978); R. G. Evans, Plasma Phys. Control. Fusion. 28, 1021 (1986); R. Betti and J. Sanz, Phys. Rev. Lett. 97, 205002 (2006).

E20339b

Magnetic-field generation has been studied in side-on and face-on geometries using the acceleration of planar targets



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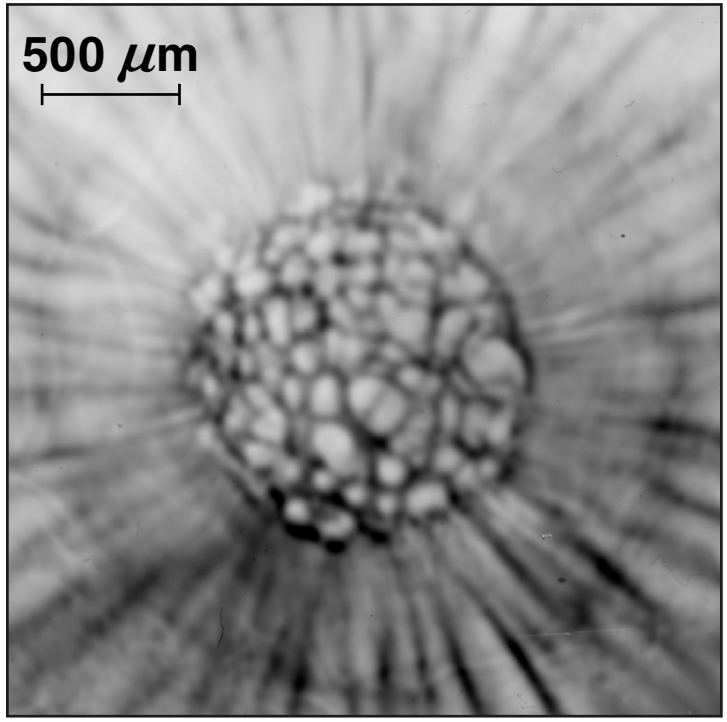
*Distributed phase plate

Face-on probing reveals magnetic-field generation by the RT instability

Proton radiograph



$t = t_0 + 2.6$ ns

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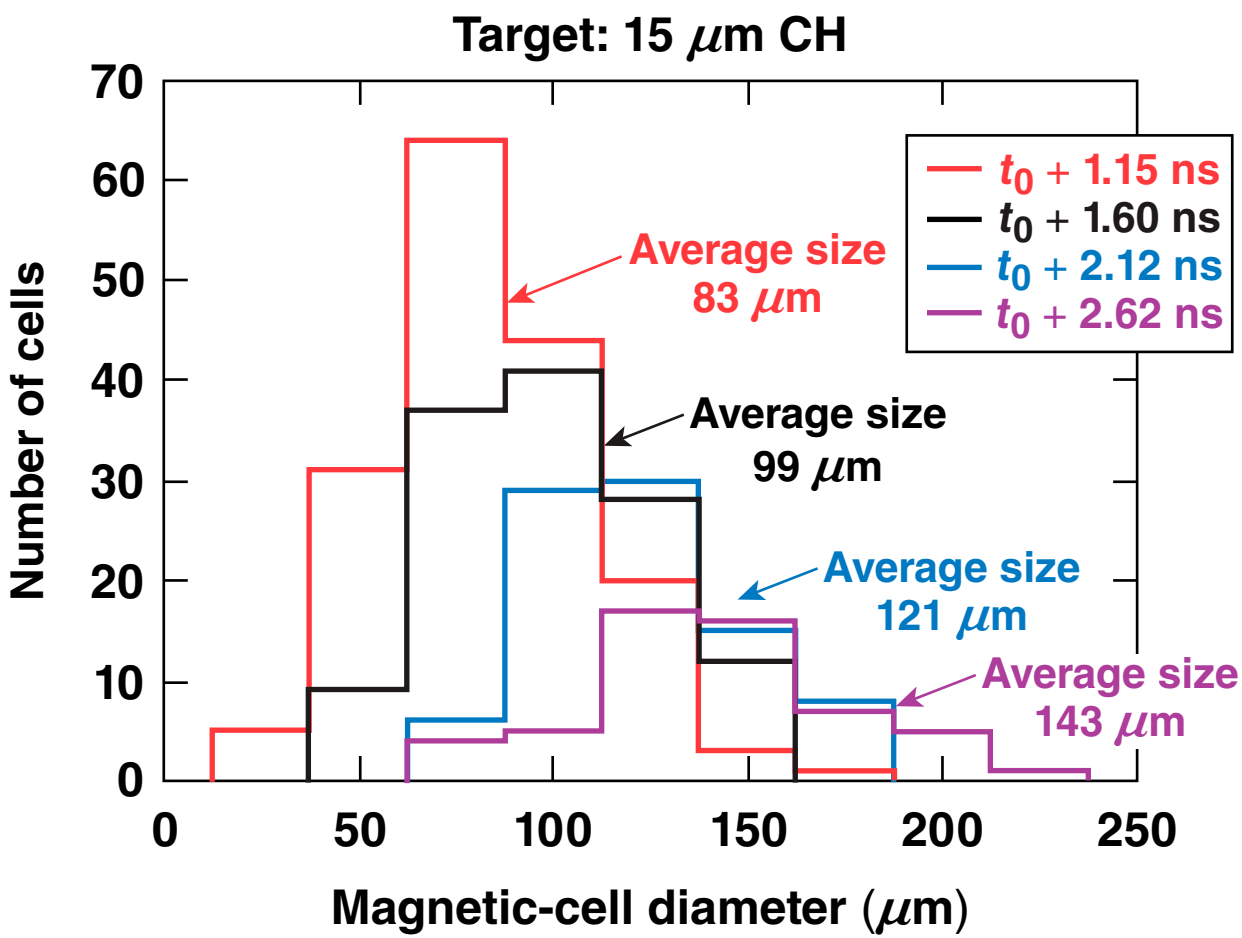
The number of magnetic cells decreases and the magnetic-cell diameter increases with time



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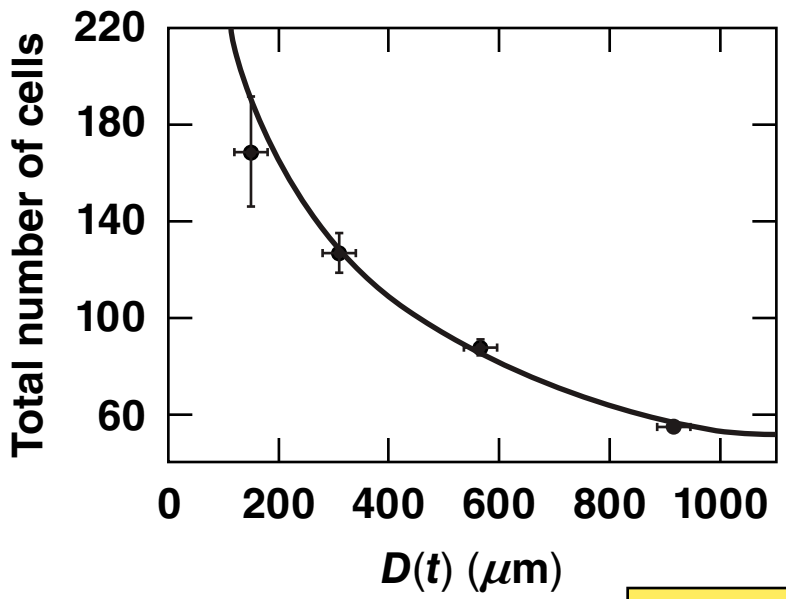
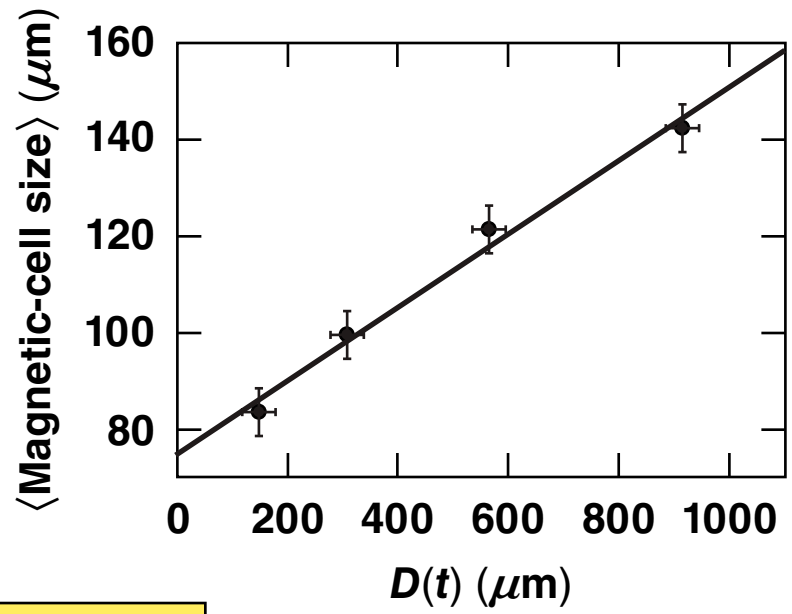
The evolution of the magnetic-field spatial distribution is consistent with an RT bubble competition and merger model*

Target: 15 μm CH

$$N(t) \propto \left(\varpi\sqrt{2D(t)} + 2C\right)^{-4}$$



$$\langle\lambda\rangle(t) \propto \varpi^2 D(t)$$

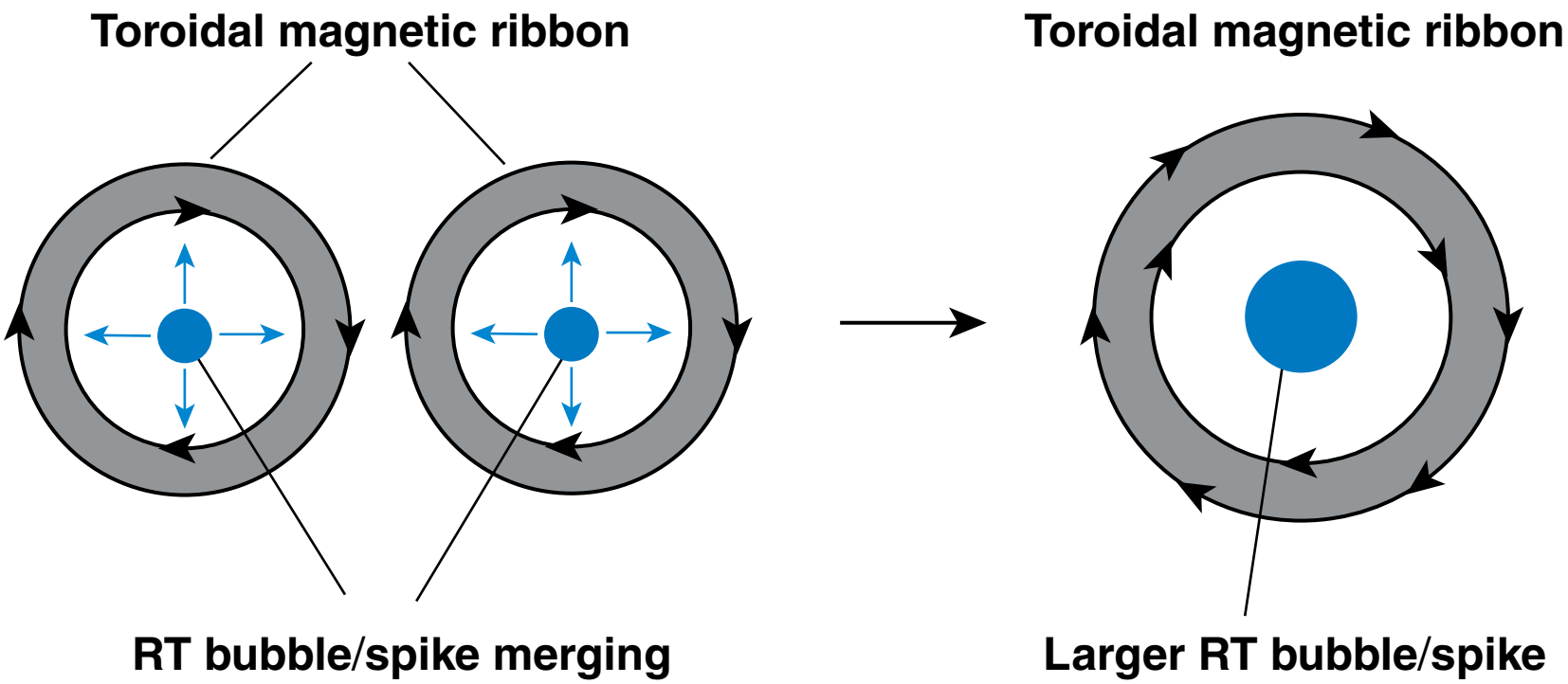


$$\varpi_{CH} = 0.79 \pm 0.06^{**}$$

*O. Sadot *et al*., Phys. Rev. Lett. 95, 265001 (2005);
D. Oron *et al*., Phys. Plasmas 8, 2883 (2001);
U. Alon *et al*., Phys. Rev. Lett. 72, 2867 (1994).
**L. Gao *et al*., Phys. Rev. Lett. 110, 185003 (2013).

E21810

Global magnetic organization occurs as a result of diffusive magnetic reconnection

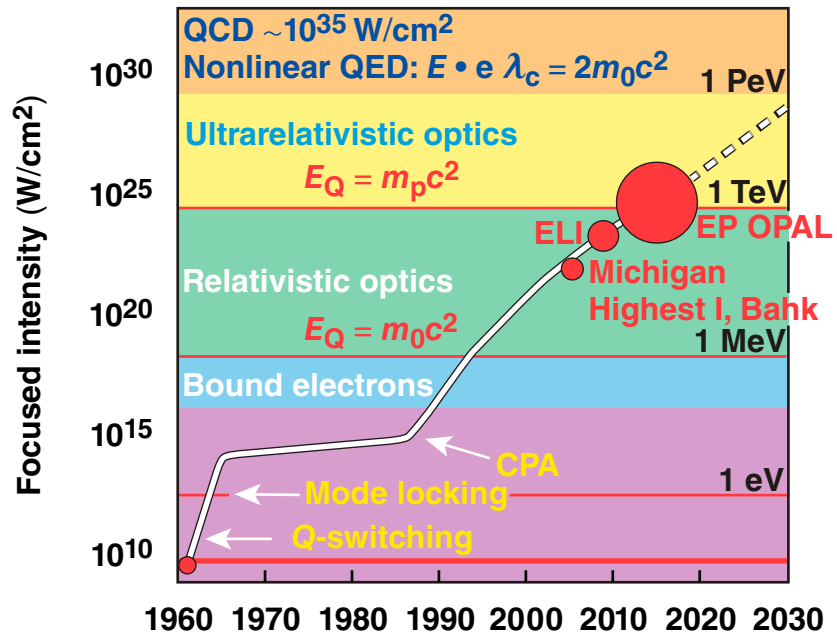


Could this be the seed source for the galactic dynamo?

E21859b

Numerous facilities around the world are being developed to increase peak laser intensity and improve diagnostics of dynamic materials properties

- Extreme Light Infrastructure (ELI) in Europe
- MaRIE at Los Alamos
- Upgrade to Materials in Extreme Conditions (MEC) at Stanford
- Dynamic Compression Sector (DCS) at Argonne National Laboratory
- Ongoing high-intensity laser development around the world



*G. A. Mourou, "Extreme Light: Bridging Optics and Fundamental High Energy Physics, First Steps Toward Zeposecond and Zettawatt Science," presented at the Institute of Optics Colloquium, 9 March 2015.

I2205

A kilojoule-class femtosecond laser with an intensity of ~10^{24} W/cm^2 would open new physics frontiers

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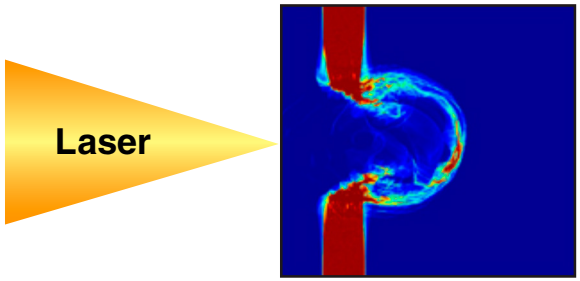
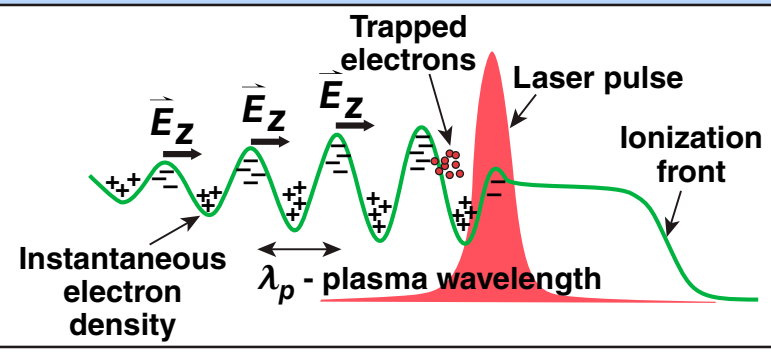
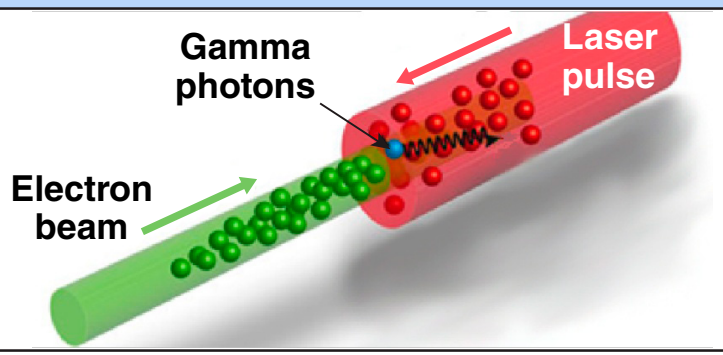
Protons – relativistic above 10^{21} W/cm^2



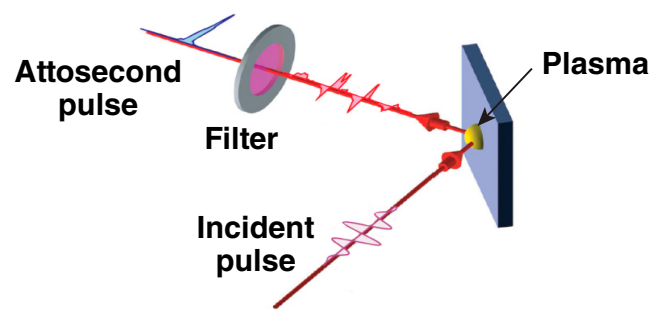
Electrons – accelerated to ≫1 GeV



Monoenergetic γ for nuclear science



Attosecond pulses from relativistic mirrors for quantum electrodynamic studies



This laser would be a world-class tool for fundamental science at new intensity regimes.

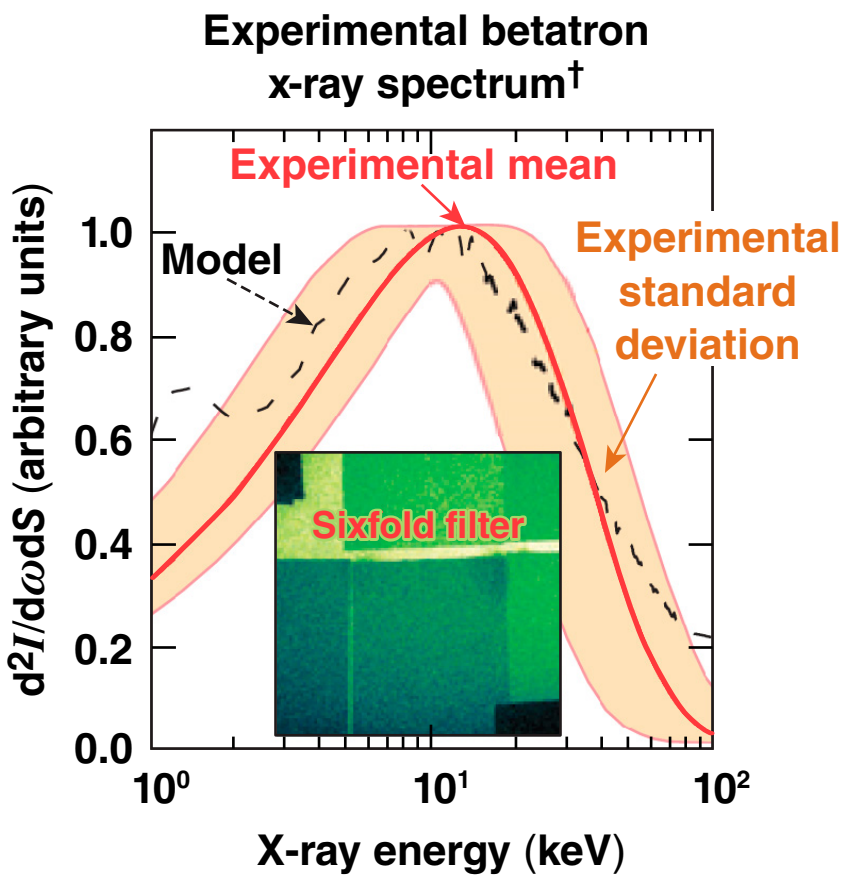
E20943e

A combination of kilojoule femtosecond, picosecond, and nanosecond beams will make a stellar materials science facility

- Nanosecond beams will
  - shock compress materials for Hugoniot equation-of-state (EOS) studies
  - ramp compress materials for off-Hugoniot EOS studies
- Picosecond beams will be used alone or with nanosecond beams to isochorically heat materials
  - either before or after compression for off-Hugoniot EOS studies
- An ultra-intense laser will generate intense x-ray and particle beams to provide unique probes of compressed materials
  - neutron and ion beams can be used for diffraction studies
  - intense line or K_α radiation from femtosecond laser–target interactions for radiography and diffraction
  - betatron sources provide broad and smooth spectra for opacity and x-ray absorption fine structure (EXAFS) studies

A kilojoule-class femtosecond laser would be a bright continuum x-ray source at proton energies of 100 keV and beyond

- Implosion-based continuum sources* are not available above ~20 keV
- Betatron sources show promise to produce tens of keV quasi-continuum x-ray sources**
- A spatially coherent, quasi-continuum, 10-keV x-ray source with a 2-J, 30-fs laser was recently demonstrated†



*B. Yaakobi *et al.*, Phys. Rev. Lett. 95, 075501 (2005).
**E. Esarey *et al.*, Phys. Rev. E 65, 056505 (2002).
†S. Kneip *et al.*, Nat. Phys. 6, 980 (2010).

E23397b

At 10^{24} W/cm^2, the quiver energy of an electron is ~100 GeV and that of a proton is ~50 MeV

- The quiver, or ponderomotive, energy is $\Phi_P = \dfrac{e^2 E_L^2}{4m\omega^2}$
- In more practical units, $\Phi_P\,(\mathrm{eV}) = 9.4 \times 10^{-14}\, I(\mathrm{W/cm^2})[\lambda(\mu\mathrm{m})]^2$
- The electrons are highly relativistic, while the protons are weakly so
- Energetic electron beams would be produced in laser–target interactions
- High-energy protons would be produced by less direct processes, but schemes are available to generate protons to much higher energies than that available with sheath-field acceleration (current limit ~60 MeV)
- Radiation pressure acceleration (RPA) becomes important when the foil thickness is decreased to approximately the laser skin depth*
  - the laser accelerates all of the target electrons within the focal volume to modest energies, accelerating all the ions in this region by space-charge forces
  - estimate ~30 GeV/nucleon with 1.6 kJ in 20 fs

*T. Esirkepov *et al.*, Phys. Rev. Lett. 92, 175003 (2004); A. Macchi *et al.*, Phys. Rev. Lett. 94, 165003 (2005).

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A kilojoule-class, 20-fs laser would provide the brightest source of attosecond (as = 10^{-18} s) pulses

- Attoseconds are the natural time scales for electrons in atoms and molecules
  - the "classical" orbital period of an electron in a hydrogen atom

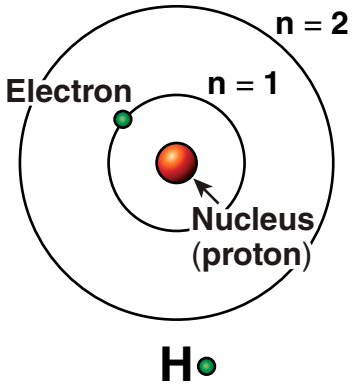
    $\hbar\omega = 13.6\ \text{eV} \Rightarrow \tau = 300\ \text{as}$

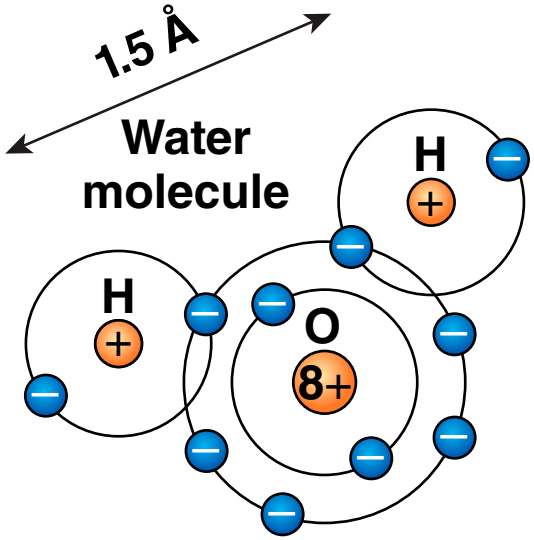
  - the time it takes light to cross a water molecule (fastest information transfer)

    $\tau = L/c \Rightarrow 0.5\ \text{as}$

  - characteristic velocities of orbital electrons involved in chemical reactions are ~ 0.005 c

    $\tau = L/(0.005\ c) \Rightarrow 100 \sim 500\ \text{as}$





Attosecond pulses probe electron dynamics in atoms and molecules—chemistry's natural time scale.

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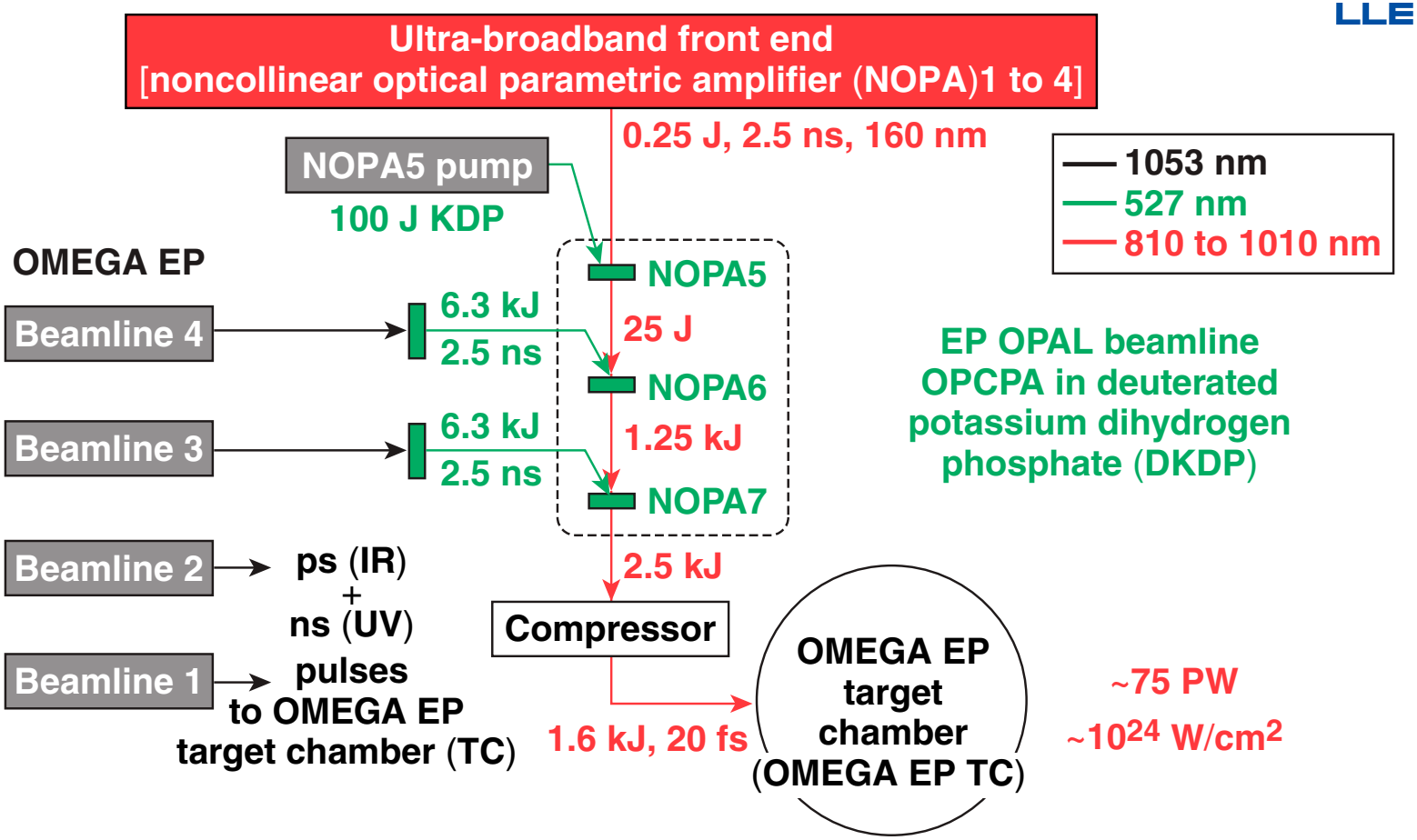
The OMEGA EP Laser System could be used to pump a 75-PW, 20-fs optical parametric chirped-pulse–amplification (OPCPA) beamline: EP OPAL



Two OMEGA EP beamlines would be used, leaving two ns/ps beamlines for pump–probe and other experiments.

E23393d

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