Perspectives on high-energy-density physics[a)]

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Much of 21st century plasma physics will involve work to produce, understand, control, and exploit very nontraditional plasmas. High-energy-density (HED) plasmas are often examples, variously involving strong Coulomb interactions and $\ll 1$ particles per Debye sphere, dominant radiation effects, and strongly relativistic or strongly quantum-mechanical behavior. Indeed, these and other modern plasma systems often fall outside the early standard theoretical definitions of "plasma." Here the specific ways in which HED plasmas differ from traditional plasmas are discussed. This is first done by comparison of important physical quantities across the parameter regime accessible by existing or contemplated experimental facilities. A specific discussion of some illustrative cases follows, including strongly radiative shocks and the production of relativistic, quasimonoenergetic beams of accelerated electrons. [DOI: 10.1063/1.3078101]

I. INTRODUCTION

The foundations of plasma physics were established in the early 20th century from studies of gaseous discharges by Langmuir, Penning, and others. Langmuir is particularly notable for inventing[1] the term "plasma" and developing, with Tonks,[2] the first theories of plasma waves. Plasma physics as a discipline emerged with the declassification[3] of magnetic fusion in 1958 and so is now 50 years old. One can observe some common features of much of the theory from the mid-20th century. Plasmas were systems with very many particles per Debye sphere. This aspect was often used as the definition of a plasma or of an "ideal" plasma. Plasmas were quasineutral. It was sufficient to do theory for pure hydrogen plasmas. Plasmas were considered to be spatially uniform and to have Maxwellian distributions. Deviations from these two assumptions drove the instabilities identified and studied during these years. Even in these early years, plasmas were often complex in ways that went beyond such simple assumptions. Indeed, any sensible definition of plasma must focus on the role of unbound or weakly bound charged particles, which is what distinguishes this state of matter from the others.

In contrast, it is fair to say that 21st century plasma physics is and will be an era of creation and control of systems that deviate strongly from the early treatment (and definitions) of plasma. Non-neutral plasmas provide an obvious example. The active tailoring of distribution functions in magnetic confinement devices could be said to be another. A large fraction of the realm of high-energy-density (HED) physics, as we shall see, lies outside the realm of ideal plasmas. Instead, HED plasmas may have extremely few particles per Debye sphere, may be composed of actively ionizing matter, may be subject to significant quantum-mechanical or relativistic effects, may involve radiation emission and absorption in essential ways, and may have Coulomb interaction energies greatly exceeding their internal kinetic energy. In the present paper we will explore these differences between ideal plasmas and HED plasmas and will look in more detail at some illustrative specific examples. First, though, let us consider how HED physics emerged as a discipline within plasma physics.

The first physicists to think seriously about ionized matter at HED were those who developed the first theories of stellar structure. In order for Eddington,[4] Chandrasekhar,[5] Schwarzschild,[6] and many others to address these problems, it was necessary to consider strongly compressed, ionized matter within which radiative energy transport was essential. The next group to carry the science further was those involved in nuclear weapon development, such as Oppenheimer, Sakharov, Teller, and Bethe. Indeed, Rhodes[7] reported that a significant conceptual barrier was to really grasp the idea that metals could be compressed, which is now a rather routine notion to students in HED physics. In this context the seminal book[8] by Zeldovich and Raizer integrated and presented a significant fraction of the knowledge in the 1960s that was relevant to HED systems. Beginning about 1960, the physics of HED systems was explored further by researchers seeking to develop inertially confined, controlled thermonuclear fusion systems, notably including Nuckolls and Emmett in the USA and Basov in the USSR. The fundamental potential of such systems was laid out[9] in Nature in 1972. Work proceeded around the world through the 1970s and beyond to develop the laser facilities or pulsed power devices that could make inertial fusion possible. This was the final element that set the stage for the distinct emergence of HED physics.

It is sensible to date HED physics as a discipline from about 1979, when there were two related developments. First, the facilities and diagnostics built for inertial fusion became sophisticated enough that one could begin to devise complex experiments intended to discover the physics of HED systems and to diagnose the resulting behavior. Second, this was the year when the first user facility program in HED physics began, specifically the "National Laser User Facility" at the Laboratory for Laser Energetics of the Uni-

a)Paper XR 2, Bull. Am. Phys. Soc. **53**, 319 (2008).
b)Invited speaker.

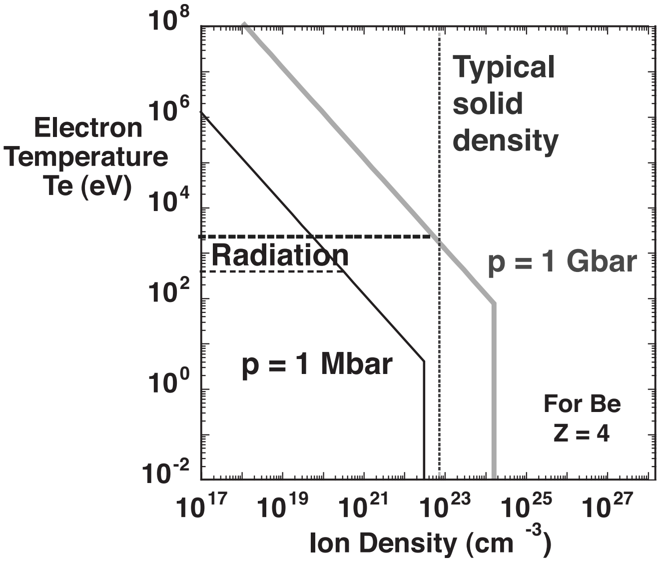

FIG. 1. Some key elements of HED physics.

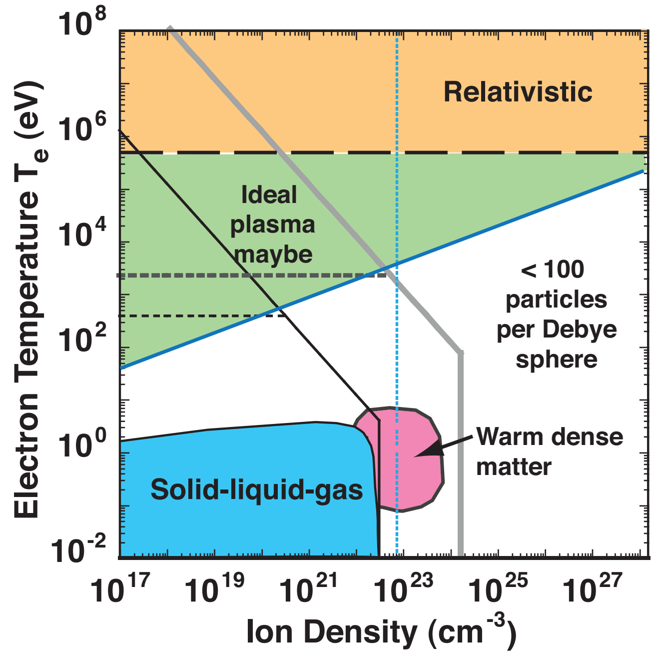

FIG. 2. (Color) Basic regimes in the space of HED physics.

versity of Rochester. A related development a few years later that significantly advanced HED physics was the rapid evolution of high-field lasers following the invention[10] of chirped pulse amplification. (Alternatively, one could date the field from 1969, when Teller and others participated in a conference[11] entitled "The Physics of High Energy Densities." The conference included a wide range of mostly theoretical discussions, save for shock physics which was then already better established. The conference anticipated future developments in several areas. The present author, however, prefers the latter date, from the point of view that the emergence of a field of physics requires sufficient experimental capability.)

II. RELATION OF HED PLASMAS TO OTHER PLASMAS

We can use Fig. 1 to orient ourselves for the discussion that follows. This figure shows electron temperature, from 0.01 to 10^8 eV, against ion density from 10^{17} to 10^{28} ions cm^{-3}. We will use these same axes for several comparisons. This space is a bit larger than the regime that can be accessed by known methods using existing or contemplated experimental facilities but much smaller than the regime portrayed in some recent reports.[12,13] The vertical dashed line shows a typical solid density of 8×10^{22} nuclei cm^{-3}. The curves on this plot and others to follow are based on a simple model found in my book[14] and applied to Be as a reminder that HED plasmas are rarely composed of hydrogen. On the expansive scale of the log-log plot, these curves are not far from where actual curves would lie. The definition of the HED regime suggested in the first report[12] was those systems whose pressure exceeds 1 Mbar (10^{11} Pa). We discuss adjustments to this definition below. The dark solid curve in Fig. 1 shows the boundary where the material pressure equals 1 Mbar. At low temperatures, such matter is Fermi degenerate, so this curve is vertical. At higher temperatures, the pressure is linearly proportional to density and temperature. For comparison, the gray solid line shows where the pressure is 1 Gbar. The solid curves do not include the radiation pressure, and thus would apply to systems from which thermal radiation readily escapes ("optically thin" systems). The dashed horizontal lines show the potential impact of radiation on the boundaries. The radiation pressures along these dashed lines are 1 Mbar and 1 Gbar. Achieving the conditions indicated by these dashed lines is far from trivial, though, whether in the laboratory or in nature. For the indicated pressures to exist, not only must the ion density and temperature be in the regime shown but also the system must be large enough to deeply trap the thermal photons within the plasma (i.e., it must be "optically thick"). In actual optically thick systems, containing both matter and radiation, the curve corresponding to a given pressure would in general move down and to the left relative to the solid curve on the plot, with how much depending on how well the radiation was trapped.

Figure 2 illustrates both some regimes within HED physics and how these relate to other physical regimes. Above temperatures of approximately 500 keV, HED plasmas are relativistic. High-field lasers routinely produce plasmas in this regime, although the electrons can only in some cases be described as both thermal and relativistic; relativistic ion plasmas remain some distance away at present. At lower temperatures is a regime where the plasma can be described as an ideal plasma. One first leaves this regime as the number of particles per Debye sphere decreases; we discuss this further below. Once the temperature decreases below about a few eV, one enters the regime of warm dense matter. In this regime, free electrons play a significant role in the dynamics but neither traditional ideal-plasma theory nor standard condensed-matter theory applies. Even so, the boundaries of the warm dense matter regime remain rather fuzzy, and no major report or scientific body has developed a definition. It

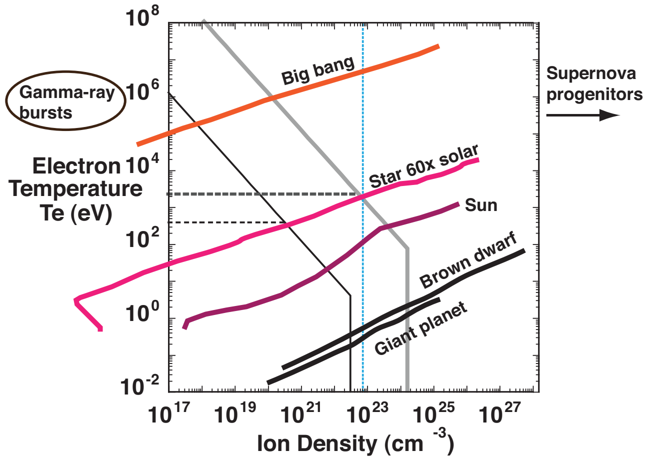

FIG. 3. (Color) Parameters of HED and astrophysical systems.

has become clear in the past decade that some such systems have pressures as low as 0.1 Mbar, but that it makes sense to consider them as HED plasmas whenever the assumptions and methods of condensed-matter theory break down. At lower temperatures and/or higher densities, warm dense matter transitions into dense matter that is very strongly Fermi degenerate. To the lower left on the plot of Fig. 2 lie solids, liquids, and gasses (the boundary shown is illustrative and not precise). Far beyond this plot to the upper right, at temperatures of order 10^9 eV and densities of order 10^{40} cm^{-3} are the quark-gluon plasmas produced in relativistic heavy-ion collisions.

The connections of HED parameters with astrophysical systems are shown in Fig. 3, with the astrophysical cases from the NRC report.[12] One can see that a wide variety of astrophysical systems exist in the HED regime, from giant planets to the big bang. Other systems, including gamma-ray bursts and supernova progenitors, are HED systems but exist beyond the boundaries of our standard plot. HED physics has connections to astrophysics beyond those seen in Fig. 3 because it may also exhibit dynamical behavior that is of astrophysical relevance. This occurs because HED systems often involve strong, fast shock waves, ionizing behavior, high-Mach-number flows, important radiation energy transport, and sometimes very strong magnetic fields. Several papers[15–17] by Ryutov *et al.* discussed the basic aspects of dynamical scaling from the laboratory to astrophysical systems.

The values of some standard parameters of plasma physics are illustrated in Fig. 4. Figure 4(a) includes curves showing the number of particles per Debye sphere, which drops far below 1 over much of our region of interest. The solid green curve shows the parameters of a system in which a laser drives a shock wave into plastic. The laser-heated corona is an ideal plasma, while the dense plasma heated by electron heat conduction or by shock heating is far from ideal. The solid red curve shows the parameters of an inertial confinement fusion (ICF) explosion at the moment of maximum compression (on the Omega laser, courtesy of Betti). Figure 4(b) illustrates that the boundaries of regimes in HED systems depend strongly on what materials are present. The more ionizing a material is, the higher the temperature boundary at which the plasma becomes nonideal. Figure 4(c) shows the boundary where the temperature equals the Fermi temperature and illustrates that the pressure in HED plasmas may not be the ideal gas value (represented as nkT, with n being the total particle density, k being the Boltzmann constant, and T being the temperature). Offsetting effects are present. Coulomb attraction tends to reduce the pressure while Fermi degeneracy tends to increase it. The values in-

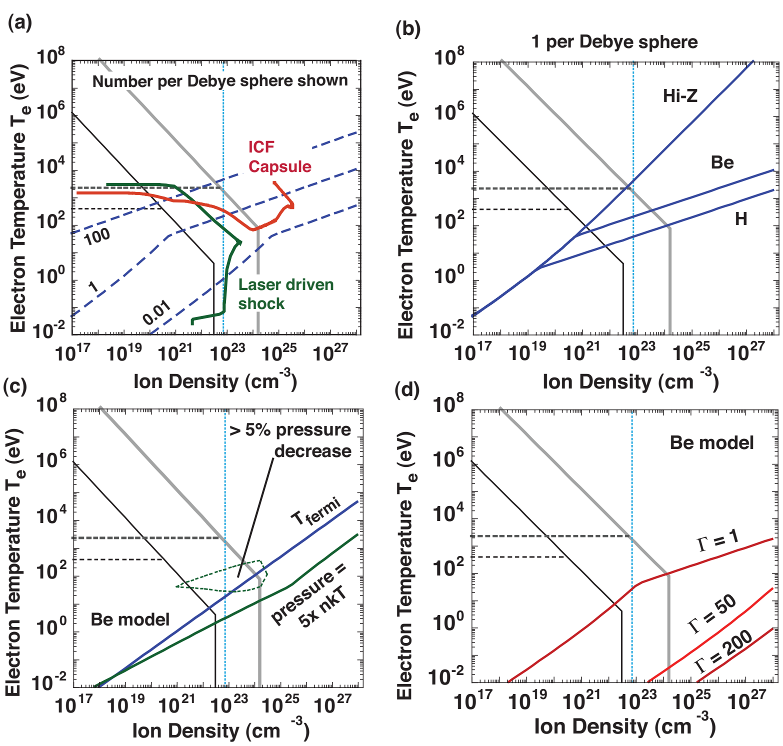

FIG. 4. (Color) (a) Particles per Debye sphere for Be, also illustrating systems with a laser-driven shock wave and a laser-driven fusion implosion. (b) The one particle per Debye sphere boundary for various systems. (c) The boundary of Fermi degeneracy and some aspects of pressure. (d) Boundaries for various values of the strong coupling parameter *G*.

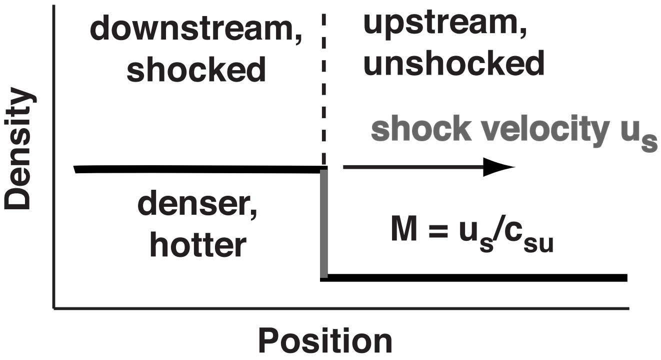

FIG. 5. Steady shock wave structure and terminology. The sound speed in the unshocked medium is c_{su}.

dicated are based on simple models for Be.[14] Figure 4(d) shows that the plasma can be strongly coupled, and perhaps very much so, across most of the Fermi degenerate regime. The strong coupling parameter Γ is the ratio of the average Coulomb potential energy between particles to the average thermal energy of a particle. One sees that the value required for formation of a crystalline structure in simple systems, of 178, might be reached in HED systems as well.

III. STRONG SHOCKS AND RADIATIVE SHOCKS

We now turn to illustrative examples, demonstrating some types of novel research that become possible in HED systems. We begin with the physics that becomes possible when one can produce very strong shocks. Indeed, it is a great challenge in any HED experiment to avoid producing strong shocks. Figure 5 illustrates the names and parameters involved in characterizing shock waves. HED facilities typically deposit 1 kJ into 1 mm^3 volume, corresponding to a pressure of the order of 10 Mbar. This will drive a shock wave into solid plastic with a shock speed u_s of roughly 30 km/s, corresponding to an "upstream Mach number" M of about 20. Such shocks are "strong shocks," having a characteristic density jump that depends on the material and having a post-hock ("downstream") pressure and temperature that scale as the square of the shock velocity. These strongly shocked plasmas often are strongly coupled, often have few particles per Debye sphere, and may involve significant radiation fluxes.

Shock waves at HED are useful in many contexts. Typical designs for ICF use three to four shock waves to compress the capsule and initiate the implosion.[18] Many equation of state experiments use one or more shock waves to alter the state of a material from an initial condition to a desired new state whose properties can be measured.[19] The shock wave itself might become unstable or might be driven into the radiative regime we will discuss in more detail here. The interaction of the shock wave with structure in the experimental medium may produce dynamics of interest, for example, the destruction of material clumps.[20] Alternatively, the shock wave may act as an intermediate energy storage medium, permitting the generation of dynamic behavior over a longer interval[21,22] or even enable isentropic compression experiments that avoid further shock generation.[23]

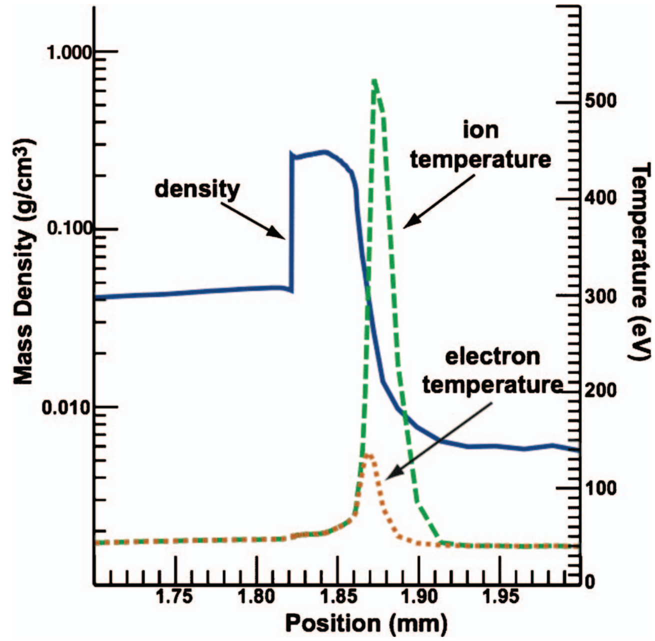

FIG. 6. (Color) Basic structure of the radiative shocks discussed here. The labels indicate the physical quantity shown by each curve.

As the shock velocity u_s increases, a shock wave in any medium will eventually become radiative. The emission from the shocked material is proportional to the thermal radiation intensity, which increases as the postshock temperature to the fourth power. Since the immediate postshock temperature is proportional to u_s^2, this radiation intensity increases as u_s^8. In contrast, the incoming energy flux increases only as u_s^3. Eventually, the radiative energy flux becomes comparable to the incoming energy flux and the structure of the shock must change in order to conserve energy. Experiments have exceeded the threshold for strong radiative effects across a wide range of parameters. They have observed structure in radiative blast waves[24–26] in Xe gas at ~10 km/s and ~10^{-5} g/cm^3. They have diagnosed in detail the radiative precursor ahead of such shocks in Xe gas[27–31] at ~50 km/s and ~10^{-3} g/cm^3 or in SiO_2 foams.[32] They have diagnosed the structure and dynamics of the shocked material[33–38] in Xe gas at ~150 km/s and ~10^{-2} g/cm^3. The have produced intense radiation sources for fusion-relevant experiments in dynamic *Hohlraums*[39] at ~300 km/s in CH foam at 10^{-2} g/cm^3.

Figure 6 illustrates the basic structure of these radiative shocks using a specific calculation for Xe gas at 0.006 g/cm^3 by the Lagrangian radiation-hydrodynamic code HYADES (Ref. 40) in one dimension. The upstream region is to the right, where there is some initial density and where the radiative precursor has established the electron and ion temperatures. The extent of this precursor in experiments reflects primarily the photon flux available to ionize the gas. The radiative energy flux returning to the region of the density jump from upstream is negligible, which is similar to the behavior in shocks emerging from stars or supernovae but not to the behavior of radiative shocks within such objects. At the shock front, the density and ion temperature increase. In the actual plasma this transition is far more abrupt than is

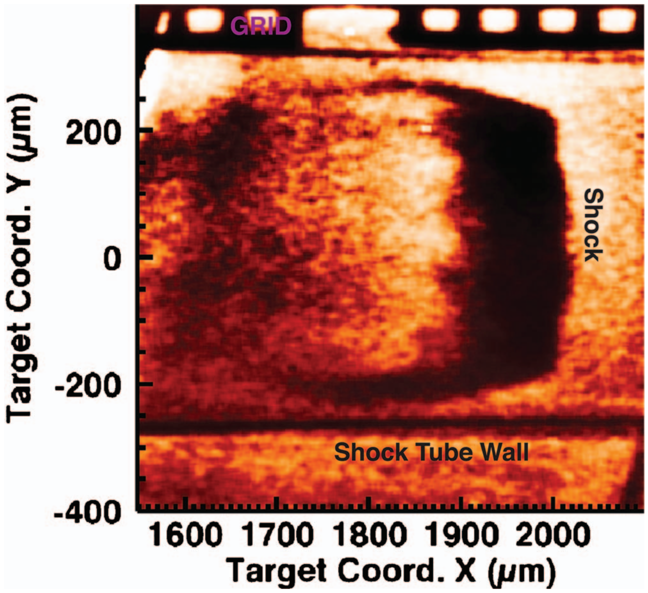

FIG. 7. (Color) Radiographic image of dense Xe layer produced by radiative shock.

seen here, where it is limited by the size of the computational zones. The ions proceed to cool by heating the electrons, which in turn begin to radiate energy, leading both electron and ion temperatures to decrease further. The density increases in response in order to maintain the required balance between the pressure in the shocked material and the "ram pressure" of the incoming flow. When there is enough of this dense material, as in the case shown, the downstream region becomes optically thick and the density and temperatures level out to steady-state values. Further to the left, the density drops abruptly at the interface where the expanding Be plasma is pushing on the dense Xe. Pressure is continuous across this interface, as it must be, even though the change in material equation of state creates a density jump.

As one example of data, Fig. 7 shows a radiographic image of a radiative shock under conditions corresponding to the simulation of Fig. 6. This image corresponds to the experiments discussed[36] by Reighard *et al.* The shock is propagating to the right down a shock tube. There is unshocked Xe to the right and Be plasma (originally accelerated by a laser) to the left of the dark layer of shocked Xe. Some detailed features of this image have motivated ongoing further study. The front and rear of the shocked layer exhibit structure, perhaps due to waves or instabilities. The edges of the shocked layer are also separated from the shock tube wall, which is not typical behavior in shock tubes. In addition, measurements of the temperature of the shocked material by x-ray Thomson scattering are underway.

IV. RELATIVISTIC LASER PLASMAS

We now turn to the HED physics that was made possible by the development of laser beams intense enough to produce relativistic oscillations of plasma electrons. For laser light of 1 μm wavelength, it requires an irradiance just above 10^{18} W/cm^2 to make electrons oscillate with a "quiver momentum" of $m_e c$, where m_e is the electron rest mass and c is the speed of light. This can be readily accomplished with a 1 J laser having a 1 ps pulse duration. At present, many lasers worldwide, operating with pulse durations from a few femtoseconds to many picoseconds and producing irradiances up to 10^{22} W/cm^2,[41] can drive relativistic electron oscillations. In addition, the beams of relativistic electrons or heavy ions produced in major accelerators typically are HED systems.[42]

Relativistic laser plasmas produce a variety of interesting and useful effects. They emit relativistic beams of electrons, typically by the breaking of strong plasma waves driven by the lasers. They produce beams of ions having energies of many MeV, which will increase to relativistic energies as more powerful lasers are developed. They produce magnetic fields at the gigagauss level and harmonics of the laser frequency so high (>200) as to become bright x-ray sources. They can produce large numbers of positrons and hold the promise of creating dense, electron-positron plasmas.[43]

Here we will focus on wakefield acceleration, where it has proven possible to produce a coherent nonlinear state in the plasma that can emit quasimonoenergetic beams of relativistic electrons, having low enough emittance to be useful in accelerators for high-energy physics. Plasma physicists are all familiar with the idea of extracting energy from a wave by riding it, which is the basis of Landau damping as it is of surfing on water. A wake is merely the wave produced by the disturbance of a medium by some passing object, such as a boat on water. If the oscillation frequency of the medium is ω and the disturbance is of a scale λ corresponding to a wavenumber k, then the phase velocity of the wake is ω/k. In the case of plasma, the relevant oscillation velocity is the plasma frequency ω_p. Tajima and Dawson realized in 1979 that by creating a disturbance in the plasma on a scale $\lambda_p = 2\pi/k_p$, so that $\omega_p/k_p \sim c$, one could hope to accelerate electrons to relativistic energies.[44] Of course, the amplitude of the wake matters as well if one hopes to obtain large electron energies. This led to a wide range of research projects aimed at cleverly inducing the plasma to develop relativistic wakes of nonlinear amplitude, for example, by driving a nonlinear resonance through the beating of two laser beams.[45–50]

Then in 2002, by means of particle in cell simulations, Pukhov and Meyer-ter-Vehn discovered what is now known as the "bubble regime." In this regime the wake is created directly by a concentration of energy so brief and so intense that it displaces a significant fraction of the electrons as it traverses the plasma. When the length and width of the disturbance are properly matched to the plasma density and length, a coherent, bubblelike structure moves across the plasma, accelerating electrons near its trailing edge into a tight beam of nearly constant energy. Figure 8 is adapted from the paper reporting this discovery.[51] It shows results corresponding to an electron quiver momentum of $10 m_e c$, produced by a 12 J, 33 fs laser pulse focused to a 12 wavelength spot and injected into a plasma of electron density of 10^{19} cm^{-3}

The corresponding physical acceleration of electrons was first accomplished by three groups using lasers to irradiate plasma produced with gas jets, with the results simul-

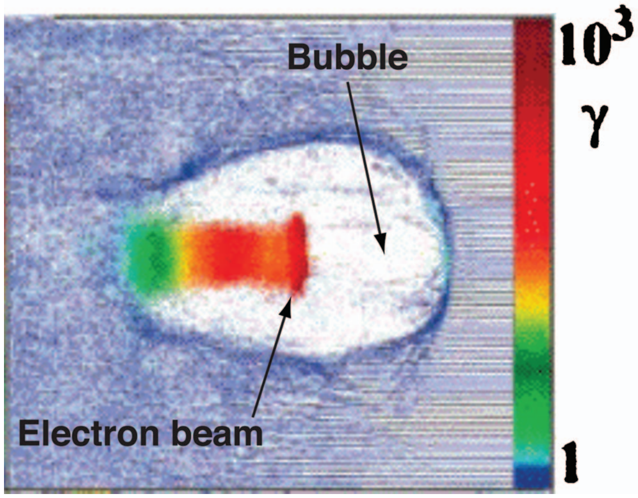

FIG. 8. (Color) Slice through simulated electron bubble, producing strongly accelerated electrons. Results are shown when the laser light has propagated 700 wavelengths.

taneously published in an issue of Nature.[52–54] Quasimonoenergetic beams having energies of ~100 MeV were produced. Subsequently, a team of researchers developed a long, uniform plasma whose density was well matched to the new short-pulse capability of the electron accelerator at the Stanford Linear Accelerator Center. They eventually managed to double the energy of some of the electrons to 85 GeV (Ref. 55) by focusing an ~50 fs long electron bunch containing 1.83×10^{10} particles to a spot size of 10 μm at the entrance of an 85 cm long column of lithium vapor with an electron density of 2.73×10^{17} cm^{-3}. Concurrently, laser-based accelerators have reached 1 GeV.[56] Figure 9 shows the energy spectrum observed in this work, in which a 40 TW, 37 fs laser pulse irradiated the plasma in a 33 mm long, 312 μm diameter capillary. Bubble-regime acceleration has important consequences for high-energy accelerators, but in the context of our present discussion consider how remarkable this state of the plasma is. One drives a large electron displacement, which typically would produce a response involving many interacting electron plasma waves, in a way that sustains a coherent structure that sweeps through the plasma. In contrast to breaking plasma waves, which typically are observed to produce electrons having broad distributions in energy and angle, this structure produces a very

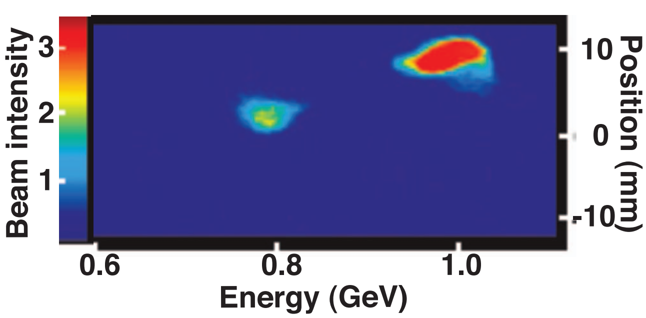

FIG. 9. (Color) A portion of the energy spectrum from a laser experiment producing a 1 GeV electron beam. Credit: Wim Leemans.

ordered, directional group of accelerated electrons. This is truly one of the marvels of plasma physics today.

ACKNOWLEDGMENTS

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