Guest Editorial

Introduction to the Special Issue on Plasma-Based High-Energy Accelerators

I. Introduction

The application of plasmas to high-energy accelerators is emerging as an exciting new area of plasma science research. Plasmas can support ultrahigh electric fields without breaking down and so offer the potential to accelerate particles in a compact device which is meters rather than kilometers long. Besides providing high-gradient acceleration, plasmas may play a number of other roles in future accelerators, such as enhancing the final focusing of particle beams. A number of plasma-based acceleration schemes have been proposed within the last decade, and recent theoretical and experimental work has begun to seriously address the plasma processes of importance to their realization. This issue should serve to update the plasma science community on the current status and recent developments in this field. Since most of the early works on plasma-based high-energy accelerators have appeared in accelerator and interdisciplinary publications and may not be familiar to the plasma science community, we shall first give a brief orientation to the subject.

To understand the interest in plasma-based accelerators one first has to look at the limits of present accelerator technology. Since the first betatrons of the 1930's, the energy attained by accelerators has increased by nearly an order of magnitude per decade (see Fig. 1), pushing the high-energy physics frontier today to the 100-GeV energy level for linear electron colliders. To continue to advance into the next decades with the present benchmark accelerating gradient (approximately 20 MeV/m) would require machines 50 km or longer. Since the walls of a conventional metallic accelerator would break down at fields exceeding this by little more than an order of magnitude, it is natural to look for new technologies with the potential for higher gradients.

Plasmas are attractive candidates for providing high accelerating gradients because they are immune from breakdown (since they are already ionized) and because plasma wave electric fields can reach large values. To estimate how large the plasma wave fields can be, consider Poisson's equation:

$$\nabla \cdot \vec{E} = -4\pi e \delta n_e$$

where δn_e is the perturbed electron density of the plasma and the ion background is assumed uniform and immobile. The largest density compression or rarefaction that can occur is roughly when all of the plasma electrons are removed. In that case $\delta n_e \simeq n_0$, the equilibrium density. Assuming a plasma wave with phase velocity near c and frequency near the plasma frequency ($\omega_p = [4\pi n_0 e^2/m]^{1/2}$) so that $k \approx \omega_p/c$ and approximating $\nabla \cdot E \sim ikE$, we obtain the maximum electric field amplitude [1]:[1]

$$eE_{\max} \sim \frac{4\pi n_0 e^2}{(\omega_p/c)} = mc\omega_p \approx \sqrt{n_0}\ \text{eV/cm}$$

where n_0 is in units of reciprocal cubic centimeters (cm^{-3}). For example, if $n_0 = 10^{18}\ \text{cm}^{-3}$, the maximum electric field is of order 1 GeV/cm, or about 3 orders of magnitude larger than the gradients in conventional linacs.

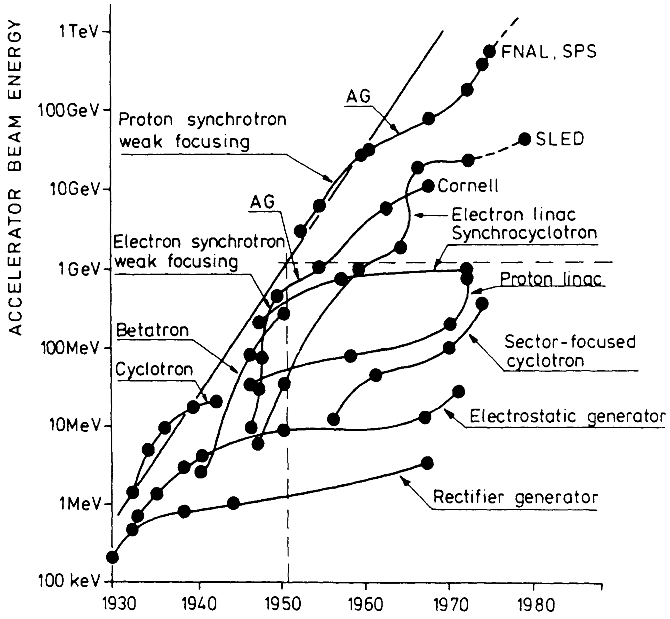

Fig. 1. The Livingston chart showing the progress in high-energy accelerators.

The papers in this Special Issue have been organized into four main topics: beat wave acceleration (laser driven), wakefield acceleration (particle-beam driven), plasma-based focusing, and magnetic field based schemes. We shall give a very brief introduction to each of these topics. For more detail the reader should consult the references cited here and in the papers which follow. The

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[1] A fully relativistic nonlinear treatment gives a larger value. See A. Akhiezer and R. Polovin, *Sov. Phys.—JETP*, vol. 3, p. 696, 1956, and J. Rosenzweig, pages 186-191 in this issue.

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conference proceedings listed in [2]-[6] may be particularly helpful.

II. Beat Wave Acceleration

The laser-driven plasma beat wave accelerator concept is the oldest and most developed of the accelerator schemes in this issue. Interest in beat wave acceleration and plasma accelerators in general [7][2] was stimulated largely by the landmark Physical Review Letter of Tajima and Dawson in 1979 [8]. Other early works on the beat wave accelerator scheme are given in [9] and in the references of W. B. Mori's paper in this issue.

In the beat wave accelerator scheme, two lasers of slightly different frequency, ω_1 and ω_2, copropagate into a plasma. If the beat frequency of the lasers ($\omega_1 - \omega_2$) is approximately equal to the plasma frequency, the ponderomotive force of the lasers resonantly excites a longitudinal plasma oscillation (in a process similar to Raman forward scattering [10]). By energy and momentum conservation of the laser photons and the plasmon, we have that

$$\omega_1 - \omega_2 = \omega_p$$

$$k_1 - k_2 = k_p.$$

If the plasma is very underdense, such that $\omega_1 \approx \omega_2 >> \omega_p$, we find that the phase velocity of the plasma wave is

$$V_{ph} = \frac{\omega_p}{k_p} = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{\Delta\omega}{\Delta k} \approx \frac{\partial\omega}{\partial k}$$
$$= V_g^{\text{light}} = c(1 - \omega_p^2/\omega^2)^{1/2}.$$

Thus the phase velocity of the plasma wave equals the group velocity of the light. The light pulse and the wake of excited plasma waves move as a unit into undisturbed plasma.

If the laser frequencies are much higher than ω_p, then V_{ph} is very close to c and injected relativistic particles may stay in phase with the electric field of the plasma wave for a sufficient distance to be accelerated to high energy. Note that this acceleration length is much greater than the coherence length of the plasma wave because the particles and laser pulse continuously outrun the onset of turbulence and plasma instabilities.

In the first paper of this Special Issue, W. B. Mori presents a detailed theoretical investigation of the growth and saturation of beat-driven plasma waves. The paper's completeness makes it an appropriate introductory review, while at the same time new results on the effects of dissipation, laser rise time, harmonics, inhomogeneities, and transverse dimensions are given. The following paper by Darrow *et al.* describes in some detail the first experiment to demonstrate the feasibility of exciting large-amplitude plasma waves with $\omega/k \approx c$ using the beat wave technique. In addition, this paper analyzes experimentally, theoretically, and with computer simulation the spurious effects which can compete with the main process: the occurrence of ion waves, slow phase velocity plasma waves, and the mode coupling among the various waves.

The next four papers address issues of critical importance to the long-term evolution of the laser pulse in the beat wave scheme. The papers by Batha and McKinstrie and Karttunen and Salomaa describe the coupling of the laser pumps to higher and lower frequency electromagnetic waves via the plasma wave (cascading). This process, which may be viewed as the continuing decay of a photon (frequency ω) into plasmons (ω_p) and lower energy photons ($\omega - \omega_p$, $\omega - 2\omega_p$, $\cdots$), ultimately determines the efficiency of the beat wave accelerator. The following paper by Sprangle *et al.* examines the self-focusing of the laser pulse in the plasma. The relativistic mass increase of the oscillating plasma electrons raises the effective index of refraction in the vicinity of the lasers. This creates a light pipe in which the lasers can propagate stably under the conditions derived in the paper. Without self-focusing, the stage length of the beat wave accelerator would be limited to the Rayleigh length over which the light diffracts. The work of Barnes *et al.* proposes a rippled plasma channel (i.e., plasma waveguide) to confine the laser and to provide a parallel component of the laser electric field for particle acceleration.

The experimental paper by Dangor *et al.* explores a mechanism for generating uniform plasmas appropriate for large-scale beat wave acceleration experiments. By multiphoton ionization of hydrogen gas with a frequency-doubled Nd glass laser, a plasma was produced which was uniform to within the measurement error of 4 percent. The next two papers address a means of enhancing the saturation amplitude of the beat-driven plasma wave by slightly ramping up the plasma density in time (actually in $t - z/c$). This is described theoretically by Matte *et al.* and the results of an interesting experiment to create a rising plasma density are presented in the accompanying paper by Martin *et al.* The final paper of this section by de Angelis *et al.* presents a possible microwave experiment which could facilitate the study of beat wave physics.

III. Wakefield Acceleration

In the scheme known as the plasma wakefield accelerator, a relativistic electron beam traverses a plasma leaving behind a wake of plasma oscillations. A trailing beam of fewer particles can then ride the plasma waves and accelerate to high energy in the same manner as in the beat wave scheme. The phase velocity of these waves is tied to the driving beam velocity (like the wake of a motorboat) rather than the group velocity of a laser pulse.

Chen *et al.* [11] first studied the plasma wakefield mechanism for single particle drivers. Ruth *et al.* [12] recognized the analogy between plasma wakefields and wakefields in conventional waveguides, enabling the application of existing wakefield formalism to the plasma case. The work of Bane *et al.* [12] made it clear that shap-

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[2] The articles listed in [7] are review articles on laser and plasma accelerators.

ing of the driving beam density profile was important for obtaining a high transformer ratio (ratio of energy gained by a trailing particle to the initial energy of a driving particle). They suggested the use of a linearly ramped driving beam. For such a ramped driving bunch, linear theory predicts the transformer ratio to be π times the length of the bunch in units of the plasma wavelength and the amplitude of the accelerating wave to be $(n_b/n_0)\, mc\omega_p/e$ where n_b is the peak driving beam density.

The four papers in the Wakefield Acceleration section of this Special Issue represent significant new contributions to this topic. The paper by J. Rosenzweig extends the wakefield analysis to the nonlinear regime where n_b is not necessarily much less than n_0. It is shown that a high transformer ratio is possible from unshaped beams (flat profile) if their density is high enough $(n_b \approx n_0/2)$. The paper by Su *et al.* examines the stability of the driving beam in the wakefield accelerator. They show that the Weibel and two-stream instabilities can be suppressed by the introduction of thermal energy spread in the beam and/or a dc magnetic field. The following paper by Keinigs *et al.* presents 2-D computer simulations in support of an upcoming proof-of-principle plasma wakefield experiment. The article by Jones and Keinigs proposes a new scheme to accelerate particles with an ion wakefield excited by a very high current electron beam. The final paper of this section by Wilks *et al.* examines beam loading in plasma waves (i.e., how many particles can be accelerated with what efficiency and beam quality). The paper is placed in this section because the analysis draws heavily on the wakefield formalism, although the results apply equally to any plasma wave accelerator scheme (e.g., the beat wave accelerator).

IV. PLASMA WAVE FOCUSING

Although the current interest in using plasma for accelerators is primarily in obtaining ultrahigh gradients, there are other ways that plasmas may impact future accelerators. One of these is the use of plasmas to focus particle beams. The two papers in this section suggest two very different ways to accomplish this.

The paper by Chen *et al.* describes a plasma focusing scheme in which a high-current beam is focused by its own radial wakefield forces in a passive plasma. The paper by Autin *et al.* describes the status of an ongoing experiment at CERN to focus antiprotons with a Z-pinch plasma. In this case the beam current is weak so the plasma must play an active role; the focusing force is provided by the azimuthal magnetic field created by the Z-pinch current.

V. MAGNETIC-FIELD-BASED SCHEMES

The last section of the Special Issue includes three papers on novel acceleration mechanisms in which a dc magnetic field plays a key role. The work of Loeb *et al.* describes electron and positron acceleration by a laser propagating along a dc magnetic field. The microwave experiment performed by Nishida *et al.* demonstrates acceleration of particles in an electromagnetic field (generated by resonance absorption) propagating across a dc magnetic field. This is the mechanism of the so-called surfatron accelerator scheme ([4] of their paper) in the nonrelativistic limit. The following paper by Takeuchi *et al.* shows that a similar type of $\vec{E} \times \vec{B}$ acceleration can be obtained in an *electromagnetic* wave propagating across $\vec{B}$.

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