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Relativistic Plasma Waves and Particle Acceleration

In the continuing search for the fundamental building blocks of matter, particle accelerators have become indispensable to physicists since the invention of the cyclotron in the 1930s. In contrast to their earliest table-top ancestor, today's synchrotrons are some of the largest machines ever built, with circumferences measured in kilometers rather than in meters. It is natural to ask, therefore, if it is possible to achieve far higher accelerating gradients than the current typical gradient of 20 MeV/m, thereby permitting machines of ever-increasing energies, but reasonable size and cost, to be built.

In any particle accelerator scheme, the basic requirement for obtaining particles with ultrahigh energies is an intense longitudinal electric field that interacts with particles for a long time. Since highly relativistic particles move at nearly the speed of light (c), the energy gained by the particles is maximum if the accelerating field is made to propagate with the particles. Extremely large electric fields propagating with phase velocities close to c can be produced by space charge waves in a plasma. The maximum electric field of such a so-called relativistic plasma wave is approximately equal to the square root of the plasma electron density per cm³. For instance, the longitudinal electric field of a relativistic plasma wave with a background density of $10^{16}$/cm³ can be as high as $10^{10}$ V/m. Such waves can be either laser-driven, as in the Plasma Beat Wave Accelerator, or excited by a short bunch of relativistic electrons, as in the Plasma Wake Field Accelerator. In both cases the plasma acts as a single-mode, slow-wave cavity, in which the wavelength of the accelerating wave is typically several hundred μm, as compared to 10 cm in linacs. This hitherto unexplored regime of parameter space may hold the key to the possible miniaturization of particle accelerators.

In the Plasma Beat Wave Accelerator, two laser beams of slightly different frequencies resonantly beat in a plasma, in such a way that their frequency and wavenumber differences correspond to the plasma wave frequency and wavenumber. The amplitude modulated beat wave exerts a periodic ponderomotive force on the plasma electrons, causing them to bunch. The resulting space charge wave has a phase velocity that is equal to the group velocity of the beating waves. If the laser frequencies are much higher than the plasma frequency, the group velocity is nearly c. If an electron is now injected with a velocity close to this, it can be trapped and accelerated by the plasma wave much in the same way as a surfer riding an ocean wave.

In the plasma wake field accelerator, a high-current but low-voltage electron bunch is used to excite the plasma wave. The phase velocity of this plasma wave (like the wake of a boat) is tied to the velocity of the driving bunch, which is close to c. This wave then accelerates a trailing low-density bunch to high voltage or energy. The plasma thus acts as a transformer, increasing the voltage at the expense of current. The key to obtaining a higher transformer ratio is to use a slowly ramped but sharply truncated driving bunch.

In both the beat wave and the wake field cases, the trick to inhibiting most of the usual laser or beam plasma instabilities is to use a driver pulse that is only a few picoseconds long. To simulate the plasma wave excitation by a finite cross-section driver pulse and to optimize the energy extraction by the accelerating beam, extensive two-dimensional particle simulations have been carried out. Theory predicts, and the simulations confirm, that the maximum energy that the particles get is limited by either the particles. Eventually outrunning the wave (dephasing) or by the pump depletion of the driver.

Experiments are underway at UCLA, Rutherford Laboratory (U.K.), ILE (Japan), INRS (Canada) and elsewhere to demonstrate the excitation of the relativistic plasma wave by the laser beat wave in a reproducible fashion and to demonstrate controlled acceleration of injected test particles. In a recent UCLA experiment, the relativistic plasma wave was excited by beating the 9.6 μm and 10.6 μm lines of a CO₂ laser, with a modest intensity of $2 \times 10^{13}$ W/cm² in a 10⁹/cm³ density plasma. The plasma wave electric field was inferred from Thomson scattering of a probe laser beam to be $10^3$ MeV/m, a substantial improvement over the current benchmark gradient for accelerators. A new mechanism which saturates the beat-excited plasma wave in this parameter regime was discovered. The relativistic plasma wave saturates, on the time scale of a few picoseconds, by coupling to other plasma modes which have a much lower phase velocity, via an ion ripple due to stimulated Brillouin scattering of the laser beams. A scaled-up experiment which will demonstrate controlled acceleration of injected electrons is currently underway at UCLA. Experiments on the wake field concept are planned at UCLA and at Wisconsin.

Finally, it is worth mentioning some of the other applications of this new research area in plasma physics. The beat-excited plasma wave may be used as an intense submillimeter wave undulator for generating tunable, short-wavelength radiation using only a modest energy electron beam. Radial electric fields of a relativistic plasma wave with a transverse dimension on the order of a wavelength can be very intense and may be useful for focusing high-energy particles in a linear collider. A beat-excited plasma may also prove to be an ideal system for studying plasma evolution from a deterministic state into turbulence.
Transport Near The Onset of Chaos

Recent research has shown that systems with only a few dynamical variables can behave in surprisingly complicated ways, which would ascribe a frictional pendulum with time-periodic forcing, is sufficient to give motion which is essentially as unpredictable as the proverbial toss coin. Similarly, an energy-conserving, or Hamiltonian, system with dynamical variables (twodegrees of freedom) is typically chaotic. Hamiltonian systems with completely regular or integrable motion can be devised, but virtually any perturbation of such a system gives a complicated mixture of regular and chaotic trajectories.

The understanding of these systems is fundamental to designing fusion devices such as tokamaks and stellerators, building efficient accelerator storage rings, determining the stability of the solar system, estimating chemical reaction rates, and many other problems.

An important example is the confinement of charged particles by a magnetic field. When the field is strong, the particle dynamics reduce to two degrees-of-freedom: gyration about the field line can be averaged out and, basically, particles follow field lines.

Since field lines never end, the confinement of particles require a toroidal configuration; if the torus is perfectly axisymmetric there is a constant of motion, associated with the symmetry, which restricts the lines to two-dimensional toroidal surfaces. Such configurations are never realizable, partly because it is impossible to build perfectly axisymmetric field coils, but more generally because of symmetry-breaking collective motions of the plasma. These imperfections cause some of the field lines to wander through three-dimensional regions of space in an extremely complicated, irregular or stochastic way. If these regions extend to the walls of the confinement device, particles will be rapidly lost.

If the chaotic regions filled the entire confinement vessel, a diffusion coefficient could be obtained from a reasonable statistical hypothesis. However, the imperfections may be small enough that many field lines remain confined; on the other hand, a significant fraction of the orbits are often chaotic.

In this transition stage the notion of smoothly diffusive motion must be abandoned; chaotic trajectories linger for long periods in the neighborhood of invariant tori, and are impeded by the remnants of barely destroyed tori. These remnants are called “cantori” because they are invariant Cantor sets (a torus minus an infinitely long ribbon which winds around with irrational rotation number). The flux of trajectories through a cantorus is a well defined quantity and can often be very small even though the cantorus itself occupies zero area.

Between the cantori, there are periodic orbits which result from resonances between frequencies of each degree of freedom. These come in stable-unstable pairs. Near stable orbits there are encircling invariant surfaces which ensure local stability. By contrast, the unstable orbits have two-dimensional stable and unstable manifolds which form a “separatrix.” The separatrix encloses the stable orbit, and the whole structure is called a “resonance.” The volume of the resonance and the flux of trajectories entering and leaving it through the separatrices are well defined quantities.

Numerical evidence indicates that resonances fill all of phase space, except that portion filled with invariant tori. This implies that phase space is divided into states, which are the resonances, separated by “fences,” the separatrices and cantori, with gates or “turnstiles” with sizes determined by the flux. Transitions from state to state can be treated statistically because a chaotic orbit diverges from its neighbors exponentially in time; initially close trajectories have wildly different futures. The divergence rate is much faster than the transition rates between resonances; thus successive transitions are nearly statistically independent.

Transition times from states near an invariant torus are arbitrarily long. This leads to the prediction that correlation functions decay algebraically with time. This theory of transport successfully predicts the escape times near onset of chaos in perturbed tokamaks. It also has been applied to the calculation of unimolecular chemical reaction rates and other situations. Numerical experiments to confirm the algebraic decay of correlations are difficult and time consuming, but so far confirm the theory.

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