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A SOLID STATE ACCELERATOR*

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ABSTRACT

We present a solid state accelerator concept utilizing particle acceleration along crystal channels by longitudinal electron plasma waves in a metal. Acceleration gradients of order 100 GV/cm are theoretically possible, but channeling radiation limits the maximum attainable energy to 10^5 TeV for protons. Beam dechanneling due to multiple scattering is substantially reduced by the high acceleration gradient. Plasma wave dissipation and generation in metals are also discussed.

Presently existing high energy particle accelerators are limited to acceleration gradients of order 10 MV/meter. This implies that to achieve ultra-high energies exceeding several TeV would require great distances. In recent years there has been an increased interest in the high-gradient linear acceleration of charged particles.[1,2] One concept which promises very high gradients is the plasma accelerator.[3] In this scheme longitudinal plasma oscillations with phase velocities near the speed of light provide large electric fields which are intended to accelerate particles to high energy over a short distance. Gradients of order $\sqrt{n}$ V/cm are theoretically possible where n is the electron number density in units of cm^{-3}. Typical laboratory plasma densities are in the range 10^{14}–10^{18} cm^{-3} corresponding to maximum gradients of 10 MV/cm–1 GV/cm.

However a high gradient is not the only requirement for linear colliders, stability and emittance requirements for the accelerating system are very stringent. Since the beams from two independent accelerators must collide at an interaction point, excessive transverse motion and emittance growth of the beams induced during acceleration must be avoided. One concern is that plasma accelerators may be prone to such beam instabilities due to plasma non-uniformities and multiple scattering.

To extend the plasma wave acceleration idea to very high gradients and avoid beam emittance degradation, we explore in this paper a solid state accelerator concept in which particles are accelerated along atomic crystal channels by plasma waves in a metal. Conduction electrons in a metal form a very uniform high density plasma exhibiting longitudinal plasma oscillations.[4] Typical conduction electron densities are of order 10^{22} cm^{-3} corresponding to a maximum gradient of order 100 GV/cm. Although this gradient equals 10^3 V/Å,

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the metal can support such high fields because the ionization energy of the atomic core electrons is at least several times the plasmon energy $\hbar\omega_p \sim 10$ eV.

For phase velocities near the speed of light, the plasma wave number $k_p = \omega_p/c \simeq 5\times10^{-3}$ Å^{-1} is much less than the Fermi wave number $k_F \sim 1$ Å^{-1} in the metal, so plasmon damping is primarily due to interband transitions (electron transitions to unfilled bands) with the decay width Γ_p being typically 10^{-1}–10^{-2} $\hbar\omega_p$.[5] To use such plasma oscillations to accelerate charged particles to very high energy is problematic since the radiation length for electrons and positrons is of order 1 cm in solids, while the nuclear collision length for protons and antiprotons is of order 10 cm.

These problems can be substantially mitigated for heavy positively charged particles ($m \gg m_e$) by utilizing the channeling phenomenon in crystals.[6] Positively charged particles are guided by the average electric fields produced by the atomic rows or planes in the crystal. The particles make a series of glancing collisions with many atoms and execute classical oscillatory motion along the interatomic channels.[7] In contrast, negatively charged particles are attracted by the atomic nuclei and suffer large angle Coulomb scatterings resulting in rapid dechanneling. This suggests that it is possible to accelerate positively charged particles on plasma waves for considerable distances through channels in metallic crystals.

Because very light particles such as positrons emit intense channeling radiation in crystals,[8] this method can only be used for accelerating heavy particles to high energy. Protons or heavy ions would be ideal candidates. Ultimately at very high energy even such massive particles will radiate, thus limiting the maximum attainable energy in such a channeling accelerator. This maximum energy is easily estimated by determining when the energy loss due to channeling radiation approaches the energy gain from the plasma wave.

A charged particle channeling through a crystal emits radiation as it oscillates transversely in the channel. At the very high energies which interest us, the channeling radiation spectrum resembles familiar synchrotron radiation[9] so the energy loss per unit length for a particle with charge ze can be written as

$$\left(\frac{dE}{dx}\right)_{ch} = -\frac{2}{3}\,\alpha z^2\,\frac{mc^2}{\lambda\!\!\!^{-}_c}\,\Upsilon^2 \quad , \tag{1}$$

where α is the fine structure constant, $\lambda\!\!\!^{-}_c$ is the reduced Compton wavelength for a particle of mass m, and Υ is a Lorentz invariant radiation parameter. For a channeling particle $\Upsilon = \gamma\,\mathcal{E}_\perp/\mathcal{E}_c$ where $\gamma = E/mc^2$, $\mathcal{E}_\perp$ is the transverse channeling electric field and $\mathcal{E}_c \equiv m^2c^3/ze\hbar$.[10] Typically the channeling fields are of order 10^2 V/Å. For protons this corresponds to $\mathcal{E}_\perp/\mathcal{E}_c \sim 10^{-13}$, and the radiated energy loss is of order the plasma acceleration gradient when the proton energy is approximately 10^5 TeV.[11]

Perhaps a more immediate concern than the energy limitation is gradual beam dechanneling.[12] The transverse momentum of channeled particles will increase due to collisions with electrons in the channel.[13] Dechanneling of beam particles occurs when their transverse kinetic energy allows them to overcome the channel potential energy barrier V_c. The increase in the transverse energy of a channeled particle with distance can be written approximately as $dE_\perp/dx = V_c/x_d$, where the characteristic dechanneling length is

$$x_d = \frac{\Lambda E}{ze} \quad . \tag{2}$$

The dechanneling constant Λ is typically 1–10 μm/MV, so high energy particles can channel considerable distances in a crystal. For example, a 1 TeV proton beam could channel of order one meter in a metallic crystal like tungstun.[14]

Beam dechanneling in a solid state accelerator is complicated by the fact that as the beam energy changes the dechanneling length x_d changes proportionally. The decrease in the channeled beam fraction f with distance can be approximately described by the decay equation,

$$\frac{df}{dx} = -\frac{f}{x_d} \quad . \tag{3}$$

For an accelerated beam, the energy is $E = E_0 + zeGx$, where G is the gradient, and E_0 is the initial energy. The dechanneling length is then $x_d(E) = \Lambda\,(E_0 + zeGx)/ze$ so the solution of Eq. (3) is

$$\frac{f}{f_0} = \left(1 + \frac{zeGx}{E_0}\right)^{-1/\Lambda G} = \left(\frac{E_0}{E}\right)^{1/\Lambda G} \quad , \tag{4}$$

where f_0 is the channeled beam fraction at $x = 0$. This expression is valid for both accelerating ($G > 0$) and decelerating ($G < 0$) relativistic beams. As an example, if a proton beam with $E_0 = 1$ TeV were accelerated one meter on a gradient $G = 100$ GV/cm in a metallic crystal with $\Lambda = 1$ μm/MV, then the surviving beam fraction would be $f/f_0 = (1/11)^{1/10} \simeq 0.8$ at a final energy of 11 TeV.

Only for acceleration gradients $G \gg \Lambda^{-1} \simeq$ 1–10 GV/cm will significant beam fractions remain channeled over long distances in a crystal. In the case of a longitudinal plasma oscillation, this implies that a large amplitude wave with a gradient of order 100 GV/cm is essential. This gradient corresponds to an energy density of order 10^8 J/cm^3, although the plasma wave would occupy at most a cross section of a few λ_p^2 ($\sim 10^{-9}$ cm^2) over a long acceleration length in the crystal. Whether the energy contained in the plasma wave is sufficient to thermally damage the crystal depends on the relaxation time for converting plasmon energy to phonons.

After the original plasma wave ($\omega = \omega_p$, $\bar{k}_p = k_p\hat{z}$) decays into interband transitions, these transitions will in turn decay into a plasmon gas with wave vectors ($|\bar{k}| \simeq k_p$) varying in direction. The plasmon gas can cause additional interband transitions but eventually electron-electron collisions will break up the plasmons as electrons are scattered out of synchronism.[5] The electron collision rate can be written approximately as $\Gamma_{ee}/\hbar \simeq 0.4[(k - k_F)/k_F]^2\, E_F/\hbar$ when the electron wave number k is near k_F.[15] Electrons in a plasmon have wave numbers $k \sim k_F + k_p/2$, so the plasmon gas decays into a hot electron gas in about 10^{-10} sec. These superthermal electrons have energies of order $10^8\ \mathrm{J\,cm^{-3}}/10^{22}\ \mathrm{cm^{-3}} \sim 100$ keV, but lose their energy at a rate of about 1 MeV/cm primarily through plasmon radiation and electron collisions. This distributes the energy of the original plasma wave radially about 1 mm among many thermal electrons which then heat the crystal by phonon emission ($\tau_{e^- - phonon} \sim 10^{-14}$–$10^{-15}$ sec). The plasma wave energy density thus decreases to about 10 J/cm^3 in 10^{-10} sec corresponding to a tolerable power input of 10^{11} W/cm^3 to the lattice. Crystal damage occurs for power inputs of order 10^{12} W/cm^3 in a nanosecond pulse.[16]

The generation of large amplitude plasma waves in a metal presumably requires an intense power source to supply the plasma wave energy in a short time without destroying the crystal. Certainly creative ideas for exciting such waves in a metal are needed. We briefly consider three possibilities, all of which are at best problematic when applied to metallic electron plasmas.

The laser beat-wave method[17] involves resonantly exciting the plasma wave by the ponderomotive force of two collinear beating lasers with frequency difference $\omega_1 - \omega_2 \simeq \omega_p$. In a metal this requires X–ray lasers with $\omega_{1,2} \gtrsim 10^{17}\ \mathrm{sec}^{-1}$. The plasmon decay width Γ_p results in the wave saturating at an amplitude $\alpha_p \equiv e\mathcal{E}_p/m\omega_p c \simeq \alpha_1\alpha_2\hbar\omega_p/2\Gamma_p$, where $\alpha_i = e\mathcal{E}_i/m\omega_i c$ are the normalized laser fields. To obtain a large amplitude wave ($\alpha_p \sim 1$) requires $\alpha_1\alpha_2 \gtrsim 10^{-2}$ or a laser intensity $I \gtrsim 10^{19}$ W/cm^2. Since this intensity is to be delivered in a 10^{-14} sec pulse with a 10^{-9} cm^2 spot size, crystal survivability is questionable.

An immediate problem with beat-wave excitation is pump depletion as the lasers leave their energy behind in plasma waves. The laser-acoustic wave scheme avoids this problem by side-injecting a laser with frequency $\omega_0 \simeq \omega_p$ into a plasma containing an acoustic wave.[18] The laser is linearly polarized along the direction of the acoustic wave vector. The laser ($\omega_0, \bar{k}_0$) and acoustic wave ($\omega_{ac}, \bar{k}_{ac}$) quasiresonantly excite forward and backward travelling plasma waves with $\omega = \omega_0 \pm \omega_{ac} \simeq \omega_p$ and $\bar{k}_p = \bar{k}_0 \pm \bar{k}_{ac} \simeq \pm\bar{k}_{ac}$. In a metal the plasma wave saturates at an amplitude $\alpha_p \simeq \alpha_0(\delta n_{ac}/n_0)\hbar\omega_p/2\Gamma_p$ where α_0 is the normalized laser field and $\delta n_{ac}/n_0$ is the acoustic wave density perturbation. To excite a large amplitude wave requires $\alpha_0\, \delta n_{ac}/n_0 \gtrsim 10^{-2}$ corresponding to an ultraviolet laser intensity of 10^{17} W/cm^2 if $\alpha_0 \sim 1/10$. The crystal may survive this high intensity because the energy would be primarily absorbed in plasmons and interband transitions within a few λ_p of the surface and only later converted to lattice heat as discussed earlier.

The wakefield method for exciting plasma waves eliminates the need for lasers by employing a charged relativistic driving beam to leave behind a wake of plasma waves.[19] The ratio of the maximum accelerating wakefield and the maximum decelerating field experienced by the driver is called the transformer ratio, $R = |\mathcal{E}^+/\mathcal{E}^-|$. For a thin driver ($L \ll \lambda_p$), $R = 2$, while for a nonsymmetric finite length driver R can be arbitrarily large.[20] In a metal collisional energy loss (1–10 MeV/cm) of the driver to electrons may destroy the crystal as the thermal electrons rapidly ($10^{-14} - 10^{-15}$ sec) heat the lattice by phonon emission. To excite a large amplitude plasma wave with a thin driver requires a surface charge density of order 10^{17} e/cm^2 whereas with a long driver a charge density of order 10^{22} e/cm^3 is required. In both cases this yields a power input to the lattice of order 10^{20} W/cm^3.

Independent of the method for exciting a plasma wave, similar considerations apply to the collisional energy loss by the accelerated beam. This will presumably limit the maximum accelerated beam current density that the crystal can withstand to approximately 10^5 A/cm^2 to avoid fracture from thermal shock. Although the channeling phenomenon and high acceleration gradient aid in maintaining the accelerated beam emittance over long distances, the collisional energy loss is a consequence of the collective nature of this solid state acceleration scheme. Certainly the scheme explored in this paper does not preclude other possibilities for accelerating particles in solids.

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