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ULTRA-HIGH GRADIENT BEAM-DRIVEN CHANNELING ACCELERATION IN HOLLOW CRYSTALLINE MEDIA

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Abstract

Since the recent discovery of the Higgs boson particle, there is an increasing demand in Energy Frontier to develop new technology for a TeV/m range of acceleration gradient with a sufficient amount of luminosity to meet the primary goals of future high energy physics. The density of charge carriers (conduction electrons) of crystals is significantly higher than that of a plasma gas, and correspondingly in principle wakefield gradients of up to 0.1 - 10 TV/m are possible. Our simulations based on Fermilab-ASTA beam parameters (50, 300, and 850 MeV and 20 pC – 3.2 nC) showed that micro-bunched electron beam gains energy to 1 – 10 MeV in the under-coupled regime ($n_b/n_p \leq 1$) and 10 – 100 MeV in the linear regime ($n_b/n_p = 1 \sim 10$) along the 100 μm long channel under the resonant coupling condition of the plasma wavelength, $\lambda_p \sim 10\mu m$. Also, with lowering a charge, electron bunches channeling through a high-density plasma medium have higher energy gain in a hollow channel than in a uniformly filled cylinder, which might be attribute to lower scattering ratios of the tunnel structure. The numerical analysis implied that synthetic crystalline plasma media (e.g. carbon nanotubes) have potential to mitigate constraint of bunch charges required for beam-driven acceleration in high density plasma media. The channeling acceleration will be tested at the Fermilab-ASTA facility.

INTRODUCTION

Charged particles, injected into a crystal orientation of a mono-crystalline (homogeneous and isotropic) target material, undergo much lower nucleus and electron scatterings and stopping power, which is commonly called the “channeling” effect. The effect has been widely investigated for accelerator particle extraction/deflection (bent crystal) and as a mean to produce X-ray radiation. The intriguing characteristic of the crystals is that intrinsically their atomic lattice spaces are rich with solid-state electrons bound to nuclei available for confined plasma wave interactions. The density of charge carriers (conduction electrons) in crystals, $n_0 \approx 10^{28} - 10^{29}$ m^{-3}, is significantly higher than what was considered in plasma gas, and correspondingly, electric fields of up to 100 GeV/cm or 10 TeV/m are possible ($E_0 = m_e c\omega_p/e \approx 96 \times n_0^{1/2}$ [eV/m], where $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency, n_0 is the ambient electron density of [m^{-3}], m_e and e are the electron mass and charge, respectively, and c is the speed of light in a vacuum). Therefore, the maximum particle energies, $E_{max} \approx (M_b/M_p)^2(\Lambda G)^{1/2}\{G/(z^3\times 100\text{ GV/cm})\}^{1/2}10^5$ TeV (M_b and M_p are the mass of the beam particle and mass of the proton respectively, Λ is the de-channeling length per unit of energy, G is the accelerating gradient, and z is the charge of the beam particle), of 0.3 TeV for electrons/positrons, 10^4 TeV for muons, and 10^6 TeV for protons can be obtained [1, 2].

The plasma wave in crystal channels can be excited with ~ 10 TV/m field amplitudes by a high energy driver, either a laser (X-ray, Bormann anomalous transmission) of 10^{19} W/cm^2 or a particle beam with power densities in the range of 10^{15} to 10^{19} W/cm^3 [3, 4]. Crystals are normally destructed at a power density of 10^{12} W/cm^3 for nanosecond-long pulses [5], which corresponds to current densities of 10^5 A/cm^2. However, in reality crystal destruction appears at 10^{13} W/cm^2 with nano-second laser pulses. The accurate dissociation point of the crystal under a given energy density will depend on the relaxation time to convert plasmon energy to phonons, but apparently the power densities seem to fairly exceed the ones of crystal fracture thresholds. It could be still possible to replace the crystal for each acceleration cycle. However, this might not be very practical. A second problem with channeling is the very small phase space of crystal channels. Only 10^5 particles would be contained in the phase space enclosed by a typical crystal channel in order to avoid crystal fracture or crystal destruction, which might provide too small luminosity for any colliding machine. All these physical issues of crystal channeling for practical application to HEP accelerators raise some interesting questions to investigate and to answer. For example, how is the channeling process degraded when a crystal is hit by an intense energy source (laser and/or particle) of 10^{12} – 10^{14} W/cm^2 power densities? Can any synthetic crystals [6, 7] designed with larger channels possibly solve all the residual problems of natural crystals in the channeling processes like extending de-channeling lengths and reducing beam and driver losses?

CNT-CHANNELING ACCELERATION

Carbon nanostructures such as carbon nanotubes (CNTs) and graphenes have various advantages for high energy channeling applications over crystals [8]; the channel size could be readily controlled up to sub-micrometers, accompanied with the larger unit-cell also capable of decreasing de-channeling rates and increasing acceptance angles. The carbon structures are comprised entirely of covalent bonds (*sp*2), which are extremely stable and thermally and mechanically stronger than crystals, steel, or even diamonds (*sp*3 bond), which will significantly improve the physical tolerance of the channels against severe thermal and mechanical impacts resulting from extremely powerful particle interactions with high power radiations and high gradient accelerations. Besides, the highly ordered carbon structures, if excited by an external driving source, can hold a single mode plasma wake that is mono-energetically coupled with channeled particles. This will lead to significantly stable channeling performances.

MODELING ANALYSIS

Charged particle interaction in solid lattice channels is asymptotically ruled by fluidic dynamics of conduction electron gas. The perturbed plasma model with plasma frequency, ω_p, and resonant density modulation can thus be effectively applied to beam-driven channeling acceleration, which could be programmed with a particle-in-cell wakefield computational platform. Figure 1 is a beam driven acceleration in the plasma channel with the solid-level plasma density, 10^{25} m^{-3} and 10^{28} m^{-3}. The simulation indicates that the charge density induces an exceptionally high acceleration gradient of 1 – 10 TeV/m as predicted by a linear plasma acceleration model.

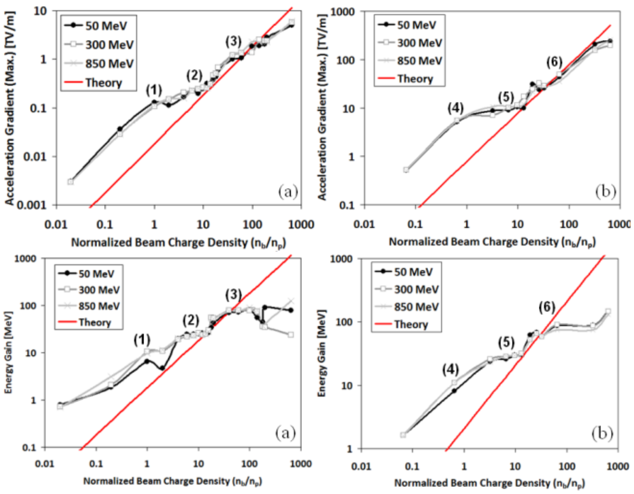
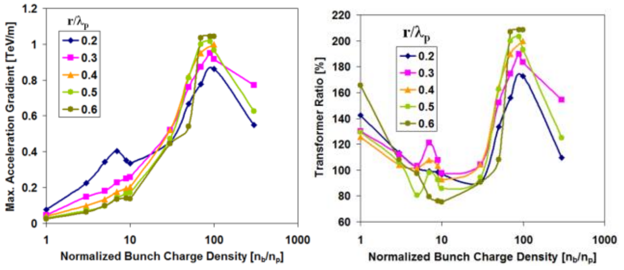


Figure 1: Acceleration gradient (top) and energy gain (bottom) versus normalized charge distribution graphs of multi-bunched drive beam with 50 MeV, 300 MeV, and 850 MeV (a) $n_p = 10^{25}$ m^{-3} and (b) $n_p = 1.6 \times 10^{28}$ m^{-3}.

In order to examine an effect of the hollow shape of CNT-structure on the channeling acceleration, we simulate beam-driven acceleration through the hollow plasma channel. For the analysis, the bunch charge density was swept from 1 to 300, normalized by plasma density, n_p, for five different tunnel radii from 0.2 to 0.6λ_p and relativistic beam energy 20 MeV (Fig. 2). While in the linear regime n_b = ~ 1 – 10n_p, the maximum acceleration gradient drops off with an increase of the tunnel radius from 0.2 to 0.6, it increased in the blowout regime, n_b = ~ 10 – 100n_p. The maximum acceleration gradient is increased from ~ 0.82 TeV/m of r = 0.2 λ_p to ~ 1.02 TeV/m of r = 0.6 λ_p with $n_b = 100n_p$, corresponding to ~ 20 % improvement. The energy transformer ratio follows a similar tendency with the acceleration gradient curve in the linear and blowout regimes. It could be explained that in the linear regime a portion of scattering energy is contributed for acceleration energy. Therefore, acceleration energy is increased as the tunnel radius gets smaller as increasing the scattering. The larger tunnel the plasma channel, however, the weaker scattering a bunch undergoes due to the decrease of repulsive space charge force. It allows a drive bunch to contain more electrons, which effectively increases a bunch charge density. Therefore, the acceleration gradient that is a function of the charge density is increased as the tunnel size is increased. In the blowout regime, the latter effect is more dominant with an increase of the bunch charge density, overwhelming the bunch scattering effect of the large charge density. This is a quite intriguing result. In the blowout regime, a hollow channel is better than a homogeneously filled one and the plasma wakefield acceleration gradient is effectively increased by enlarging the tunnel size. This result opens the possibility of controlling beam parameters of plasma accelerators for higher gradient and large energy conversion efficiency.



(a) (b)

Figure 2: (a) maximum acceleration gradient and (b) transformer ratio versus bunch charge distribution normalized by bunch charge density with various tunnel radii (r = 0.2 – 0.6λ_p)

Considering nanofabrication feasibility of a CNT-channel and affordable beam parameters, we consider n_p ~ 10^{23} m^{-3} (n_p: ambient charge density of effective plasma (electron) density) for simulation modeling analysis. This density corresponds to λ_p (plasma wavelength) ~ 100 μm and in principle it will generate a ~ 30 GeV/m gradient at the plasma-beam resonance condition in the linear regime (n_b ~ n_p: n_b is the bunch charge density). With more relaxed (or more realistic) beam conditions (n_b/n_p ~ 0.01), our simulation predicted that the channel would hold a ~ 3 GeV/m acceleration gradient with σ ~ 1 ps, 1 nC electron bunch (50 MeV) modulated with f_{mb} ~ 3 THz (λ_{mb} ~ 100μm) at the off-resonance condition. This beam parameter is well suited for a proof-of-concept experiment at the beam-test facility (Advanced Superconducting Test Facility (ASTA) at Fermilab). Test samples for CNT-channeling experiments will be fabricated by implanting straight multi-wall CNTs in an anodic aluminum oxide (AAO) template, the so-called "AAO-CNT" [9]. The AAO-CNT technique provides exceptionally uniform and straight nano-size channels and the wall thickness and crystallinity of the CNTs can be readily controlled by adjusting chemical vapor deposition (CVD) conditions.

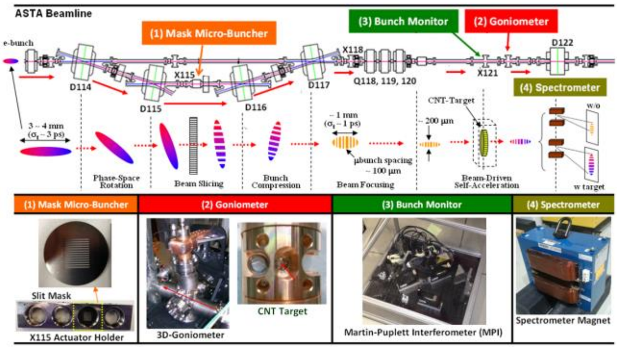


Figure 3: Channelling acceleration test setup at the ASTA beamline

EXPERIMENTAL STATUS/PLAN

In the process of beam-driven self-acceleration, a bunch head (driver) loses energy, while a bunch tail (witness) gains energy (transformer ratio = max. energy gain/max. energy loss). In the acceleration experiment, an electron bunch is compressed down from $\sigma_t \sim 3$ ps to ~ 1 ps by the bunch compressor (BC1) and focused by the triple quadrupoles until the beam spot size reaches $\sigma_r \sim 200$ μm at the goniometer position (X124). The beam is then injected into a target mounted in the goniometer and beam energy is measured by the magnetic spectrometer (D122), as shown in Fig. 3. With the plan to detect any acceleration of particle energy due to presence of a CNT channel, we will compare the beam energies measured with and without a CNT-target. Any noticeable change of the bunch shape projected to the spectrometer screen (D122) before and after loading a target will be a good indicator of channeling interaction.

It is planned with more systematic channeling acceleration tests to accurately measure the acceleration parameters (energy gain/loss, transformer ratio, etc) of the modulated bunches: first the beam energy will be measured without a target, which will be used as a reference. With a crystal target installed, electron energies will be measured in terms of the beam injection angles with respect to the target axis, as energy gain varies with the channeling angle (= injection angle). Subtracting minimum from maximum energy, calibrated by the measured data without a target, will provide the net energy gain of a CNT-crystal. We will sweep the angles with measuring the beam energies by the spectrometer and a difference between maximum and minimum values of the scanned beam energies will equal the net energy gain. With scanning bunch charges and RF-phases, the test will be repeated with a slit-mask at X115 to examine beam-modulation effects on the channeling acceleration.

SUMMARY/CONCLUSION

In summary, we have parametrically analyzed a wide range of beam-driven wakefield acceleration in extremely dense plasma channels excessively higher than a typical density level, 10^{16} – 10^{18} m^{-3}, of ionized gas plasmas, which usually limits obtainable acceleration gradient below 100 GeV/m. In dynamic plasma theory, an ultra-high electric field in TeV/m scale can be produced by a 10^{22} – 10^{28} m^{-3} range of plasma density. The numerical analysis with a plasma wakefield simulator, designed with dynamic PIC-computational platform, showed a TeV/m range of a single-bunch driver and a multi-bunched driver beam with plasma under optimized coupling conditions in the under-coupled, linear, and blowout regimes, which agreed well with the linear plasma theory. It turned out that in the dense plasma interaction, a hollow channel is more efficient in controlling beam parameters and increasing the acceleration gradient and transformer ratio in the blowout regime. The beam-driven channeling acceleration in hollow crystalline media with exceptionally high acceptance is a viable concept to realistically achieve a TeV/m level acceleration gradient.

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REFERENCES

[1] Dodin I Y, Fisch N J Phys. Plasmas 15 103105 (2008)
[2] P. Chen and R. Noble, "Channel Particle Acceleration By Plasma Waves in Metals", slac-pub-4187
[3] T. Tajima and M. Cavenago, Inst. for Fusion Studies (Texas) Preprint (1987).
[4] Y. M. Shin, D. A. Still, and V. Shiltsev, "X-ray Driven Channeling Acceleration in Crystals and Carbon Nanotubes", Phys. Plasmas 20, 123106 (2013)
[5] V.V. Belotshitskii and M.A. Kumakhov, Sov. Phys. Dokl. 24 (1979) 916.
[6] J. M. Newsam, Science 231 (1986) 1093
[7] B.S. Elman, G. Braunstein, M.S. Dresselhaus and G. Dresselhaus, T. Venkatesan, and B. Wilkens, J. Appl. Phys. 56 (1984) 2114; D. Schroyen, M. Bruggeman, I. Dezsi and G. Langouche, Nucl. Instr. and Meth. B15 (1986) 341
[8] M. Murakami, and T. Tanaka, APL 102, 163101 (2013)
[9] H. PengXiang, L. Chang, S. Chao, and C. HuiMing, Chinese Science Bulletin 57, 187 (2012)