CRYSTAL CHANNELING ACCELERATION RESEARCH FOR HIGH ENERGY LINEAR COLLIDER AT ASTA FACILITY

[1, 2]Young-Min Shin, [2]Jayakar C. Tobin, [2]Dean A. Still, [2]Kermit Carlson, [2]Michael Church, and [2]Vladimir Shiltsev

[1]Department of Physics, Northern Illinois University, Dekalb, IL, 60115, USA

[2]Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA

Abstract

Crystal channeling technology has offered various opportunities in accelerator community with a viability of ultrahigh gradient (TV/m) acceleration for future HEP collider in Energy Frontier. The major challenge of the channeling acceleration is that ultimate acceleration gradients might require relativistic intensities at hard x-ray regime (~ 40 keV), exceeding those conceivable for x-rays as of today, though x-ray lasers can efficiently excite solid plasma and accelerate particles inside a crystal channel. Moreover, only disposable crystal accelerators are possible at such high externally excited fields which would exceed the ionization thresholds destroying the atomic structure, so acceleration will take place only in a short time before full dissociation of the lattice. Carbon-based nanostructures have great potential with a wide range of flexibility and superior physical strength, which can be applied to channeling acceleration. This paper present beam-driven channeling acceleration concept with CNTs and discuss feasible experiments with the Advanced Superconducting Test Area (ASTA) in Fermilab and beyond.

INTRODUCTION

The cost models of the modern colliders are quite complicated, but one may safely assume that a future facility should not exceed a few tens of km in length and simultaneously require less than 10 to a few tens of MW of beam. To get to the energies of interest within the given footprint, fast particle acceleration is inevitable. Plasma-wakefield acceleration (PWA) has become of great interest because of the promise to offer extremely large acceleration gradients, on the order of $E_0 \approx n_0^{1/2}$ [GeV/m], where n_0 is the ambient electron number density (n_0 [10^{18}cm^{-3}]), on the order of 30-100 GV/m at plasma densities of $n_0 = 10^{17} - 10^{18}$ cm^{-3}.[1] The density of charge carriers (conduction electrons) in solids $n_0 = \sim 10^{20} - 10^{23}$ cm^{-3} is significantly higher than what was considered above in plasma, and correspondingly, wakefields of up to 100 GeV/cm or 10 TV/m are possible. In the solid plasma, as escaping from a driving field due to fast pitch-angle diffusion resulting from increased scattering rates, particles must be accelerated along major crystallographic directions. This is called “channeling acceleration”. Normally, crystal channeling has been applied to high energy beam control such as collimation, bending, and refraction [2]. For high energy beam optics, carbon nanotubes (CNTs) have been considered for bending and collimation [3,4,5]on account of the much wider range of flexibility, including superior physical strength, which also ideally fits with channeling acceleration. CNTs, composed of graphene sheets rolled into seamless hollow cylinders with diameters ranging from 1nm to about sub-micron, exhibit unique physical and chemical properties as a quasi-one dimensional material[6 ,7,8,9]. In principle, both straight and bent CNTs can effectively be used for high-energy particle channeling [10], provided the technological challenge of achieving an almost perfect alignment of CNTs with respect to the beam direction could be tackled effectively in the synthesis of samples.

Recently, Fermilab built the Advanced Superconducting Test Accelerator (ASTA) facility (50 MeV and several hundreds of MeV energy beams) that will enable a broad range of electron beam-based experiments to study fundamental limitations to beam intensity and to developing transformative approaches to particle-beam generation, acceleration and manipulation, which is ideally suited for the channeling acceleration experiment. We plan to detect a measurable energy gain from the electron bunches passing through CNTs. Successful demonstration of the experiment with this beam driven method will verify the viability of CNT channeling interaction for ultra-high gradient acceleration, which will also prove the feasibility of the laser-driven channeling acceleration. The experimental setup will be accommodated to a 50 MeV main stream beamline and high energy (50 – 300 MeV) beamline in our plan. In the research, beam energies and radiation spectra of CNT samples will be mainly characterized by beam tests at relativistic regimes.

CHANNELING ACCELERATION

Plasma acceleration provides the highest acceleration gradient ($E_0 = m_e c\omega_p/e \approx 100 \times n_0^{1/2}$ [GeV/m], where n_0 is the ambient plasma density (n_0 [10^{18}cm^{-3}]), corresponding to 30 – 100 GV/m. The density of charge carriers (conduction electrons, $n_0 \sim 10^{20-23}$ cm^{-3}) in solid media is 3 ~ 5 orders of magnitude higher than those in gaseous plasma, so in principle, a wakefield of 0.3 – 30 TeV/m can be created in crystals, which consists of the longitudinal component, $\varepsilon_z \approx - 8eN/a^2(1 - r^2/a^2)\cos(kz - \omega_p t)$, for acceleration and a transverse component, $\varepsilon_z \approx - 16eN/a^2(r/ka^2)\sin(kz - \omega_p t)$, for beam focusing ($N$: the number of electrons and a : the beam spot size).

ISBN 978-3-95450-126-7

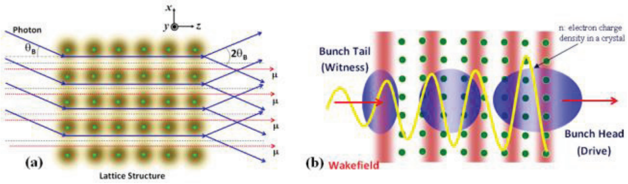

Figure 1: (a) Laser (x-ray) driven acceleration (muon, proton) (b) beam-driven acceleration (electron).

Wakefields in crystals can be excited by two sorts of driving sources: x-ray laser (Fig. 1(a)) or short electron bunch (Fig. 1(b)). With the x-ray pumping method [11], a crystal channel can hold > 10^{13} V/cm transverse and 10^9 V/cm longitudinal fields of diffracted traveling EM-waves at the Bragg diffraction condition ($\lambda/2b = \sin\theta_B$), where b is the lattice constant and θ_B is the diffraction angle) However, to hold the ultimate gradients, the acceleration requires coherent hard x-rays ($\hbar\omega \approx 40$ keV) of ≥ 3 GW to compensate for radiation losses, which exceed those conceivable today. The x-ray driving method thus fits for heavy particles, e.g. muons and protons, which have relatively smaller radiation losses. For electrons, the beam-driven acceleration is more favorably applicable to channeling acceleration as the energy losses of a drive beam can be transformed into acceleration energy of a witness beam [12]. The highly intensive plasma interaction in a crystal channel induces thermal radiations and collisional impacts accompanied by a large amount of heat energy, which would exceed the ionization thresholds and may even destroy the atomic structure. Only disposable forms of crystals such as fibers or films can be used for channeling acceleration. Also, lattice structures of crystals have fixed atomic dimensions, which thereby have some limits in designing acceleration parameters to mitigate physical constraints in solid plasma channels. Carbon nanostructures have potential advantages over crystals for channeling acceleration such as wider channels (weaker de-channeling), broader beams (using nanotube ropes), wider acceptance angles (< 0.1 rad), 3D beam control over greater lengths, and in particular excellent thermal and mechanical strength, which are ideally fit to channeling acceleration and cooling applications, plus beam extraction, steering, and collimation. CNTs are comprised entirely of *sp*2 bonds, which are extremely stable and thermally and mechanically stronger than crystals, steels, and even diamonds (*sp*3 bond). Nanotubes thus have a higher probability of surviving in an extremely intense channeling, radiation, and acceleration environment.

Plasma frequencies of CNTs are normally in the THz range, which need a beam bunch duration within an order of microns for wakefield generation in the linear regime, an electron bunch in the pico-second range, which is readily obtained from conventional RF photoemission technique, would need to be either compressed down to an order of a femto-second or split into microbunches. It is well known that injecting a driver beam with multiple microbunches in a plasma channel improves field gradient, transformer ratio, and energy efficiency of plasma wakefield acceleration. With the multiple microbunches, phase matching conditions between a plasma wave and a modulated beam can be selectively tuned in order to maximize wakefield, transformer ratio, or energy efficiency.

SIMULATION ANALYSIS

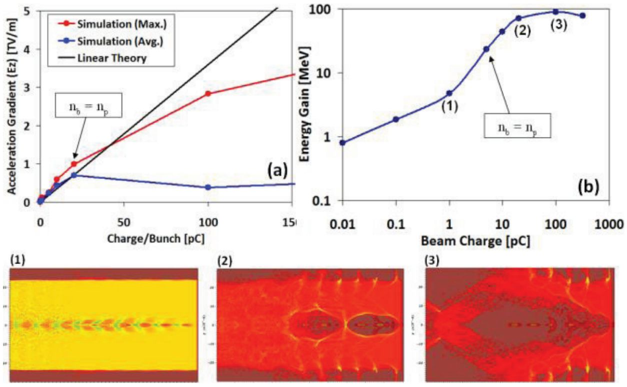

Figure 2: Channeling acceleration analysis, obtained from the linear wakefield theory and computer simulations: top - (a) acceleration gradients and (b) energy gain versus beam charge and bottom - spatial charge distributions of plasma and beam (1) 10 pC (2) 200 pC (3) 1 nC.

The basic pattern of channeling acceleration has been analyzed by theoretical model and computer simulation with the nominal ASTA beam parameters: bunch-to-bunch space = 10 μm, beam energy = 50 MeV, charge density of plasma channel = 10^{25} m^{-1}, bunch length = 2 ~ 3μm. Figure 2 shows summarized acceleration gradient and energy gain graphs with respect to beam charges, obtained from the 1D linear wakefield theory and plasma accelerating simulator (VORPAL). The simulation data agree well with the theoretical graph in the linear regime. This result clearly verifies that micro-spaced electron bunches gain energy up to ~ 70 MeV (~ 200 pC) along a 100 μm long channel, corresponding to a ~ 0.7 TeV/m acceleration gradient. The analysis indicates that further increase of the beam charge excessively blows out the ambient plasma charges in the channel ((3) of Fig. 3: bottom). It strongly pushes plasma waves out of phase-synchronization with the beam wave, which rather decreases the energy gain. The analyzed parameters will be implemented into the design process of the experimental setup. This kind of simulation method will be continuously used to analyze/design the beam-driven accelerator with various channeling conditions.

EXPERIEMNTAL LAYOUT

Preparation of Test Samples

Two kinds of channeling accelerator structures, crystals (silicon or diamond) and arrayed CNT bundles, will be manufactured and tested and compared in the first experiment. Crystal samples will be obtained by a similar fabrication technique used for silicon samples in

ISBN 978-3-95450-126-7

channeling experiments in Tevatron of Fermilab: cleaved and cut silicon wafers [13]. The sample holder, used for the experiment, will also be re-used for crystal acceleration tests, but only with the straight section (no bending). A test device with a straight multi-wall CNT bundle will be prepared using an anodic aluminum oxide (AAO) template (Fig. 3(a)) [14]. The template carbonization method consists of carbonization of an organic gas or polymer in nano-space of an inorganic template and liberation of the deposited carbon from the template. CNT synthesis technique with the anodic aluminum oxide (AAO) template provides uniform and straight nano-size channels with a tailored length and diameter (Fig. 3(b)). The length, diameter, and density of the as-synthesized CNTs can be uniformly tailored because of the controllability of the pore texture of AAO template. Furthermore, the wall thickness and crystallinity of the CNTs can be controlled by adjusting CVD conditions. We plan to test a 100 μm long, 200 nm wide CNT structure first, which may possibly be manufactured within 2 ~ 3 months. It is expected that these types of crystal channels induce plasmonic waves of $\lambda_p \leq \sim 10$ μm.

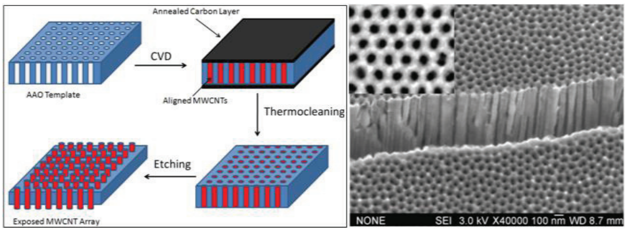

Figure 3: (a) Schematic diagram of an AAO template process (b) SEM image of an AAO film, inset is the enlarged SEM image.

High Energy Channeling Experiments at ASTA

Experiment Configuration As we plan to conduct the 1st experiment at 50 MeV beamline of the Fermilab-ASTA, test equipment will be installed downstream of the capture cavity-2 (CC-2) and bunch compressor before the 1st cryomodule. Figure 6 shows the beam line drawing, describing the currently planned location of the proposed experiment. The boxed areas indicate prospective locations of the vacuum-compatible goniometer to be loaded with a test sample. While passing through the BC, the slit-mask placed in the BC will produce microbunch trains by imprinting the shadow of a periodic mask onto a bunch with a correlated energy spread. Once passing through a test device in the goniometer, beam energies will be measured by a spectrometer with a dipole magnet and yttrium aluminum garnet (YAG) screen positioned in the beamline toward a beam dump. A test with higher energy beams is also planned, so the experiment will be accommodated to the 300 MeV beamline (Fig. 4). In the experimental configuration, the 1st cryomodule will boost the beam energy of electron bunches up to 300 MeV, which will be subsequently injected to a test sample located after a FEL undulator/chicane.

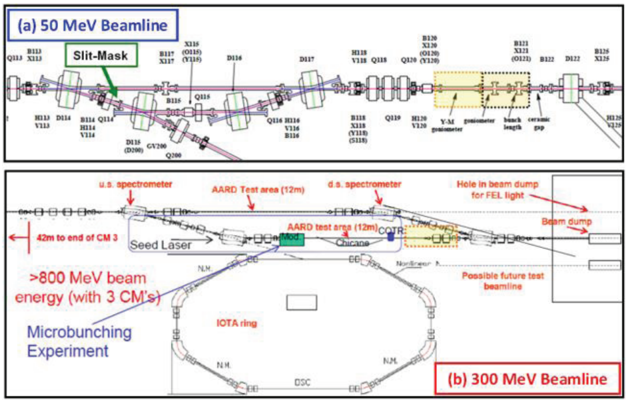

Figure 4: Prospective locations of experiment setup: 50 MeV beam line (top) and 300 MeV (bottom).

Generation of Multiple Micro-bunches For micro-bunch generation, we mainly consider the slit-mask technique, which is the simplest way to create multiple sub-ps micro-bunches. This idea is a proven technique as the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) already demonstrated the generation of a stable train of microbunches with a controllable sub-picosecond delay [15]. The shadow of the mask is converted into a time pattern when entering the dispersion-free region of the beam line. We will measure this time pattern using coherent transition radiation (CTR) interferometry. This method can be easily implemented in the 50 MeV beam line with the chicane, designed with bending angle (α) of 18° and $R_{56} \sim -0.19$ m (bending radius ~ 0.65 m).

We also plan to employ an inverse free electron lasing technique for micro-bunch generation. The longitudinally sinusoidal-dependent static magnetic field inside the wiggler causes a perpendicular force on the beam electrons and initiates electron motion in the transverse plane. Using this transverse motion the electron beam can be coupled to the laser pulse (by tuning the wiggler field period) such that some electrons feel the decelerating electric field of the laser and others the accelerating field. This picture of half-acceleration and half-deceleration repeats over every laser period along the beam length and results in a velocity modulation of the beam electrons. After the exit of the wiggler, the beam is left to propagate in a vacuum over some specific distance, after which the low-velocity electrons have caught up with the high-velocity electrons thus creating microbunches, separated at the laser's wavelength. Currently, a laser-induced microbunching (LIM) scheme with the FEL undulator is proposed in the ASTA stewardship program, which is potentially employed to generate microbunches to the channeling acceleration test.

Diagnostics and Measurement

The proposed experimental scheme will need several positions to monitor bunch profiles and measure their spatiotemporal radiation patterns and energy spectra of accelerated beams. We measure the time pattern of a

ISBN 978-3-95450-126-7

masked beam entering the dispersion-free region of the beam line using coherent transmission radiation (CTR) interferometry. The broadband transition radiation emitted by the electrons when entering a copper mirror placed after the dogleg, near the experimental region, is sent to a Martin-Puplett interferometer. Figure 5 shows a schematic diagram of the experimental arrangement used for acceleration measurements. After the energy-analyzed and collimated beam of electrons is transported through the bunch compressor into the experimental area, it is defocused by an asymmetrically split quadrupole triplet to give a low-divergence (nearly parallel) beam incident upon the crystal in its goniometer. A critical factor in performing channeling acceleration experiments is the divergence of the incident beam. Since the characteristic angle for the process is $1/\gamma$, an angular resolution at least an order of magnitude smaller is required in order to obtain data of sufficient precision to compare with the results of theoretical calculations; for $\gamma \sim 100$, a beam divergence larger than 1 mrad is inadequate. Moreover, the critical angle for channeling is a few mrad for electrons of a few tens of MeV, and varies as $\gamma^{-1/2}$; therefore, in order that a large fraction of the beam be channeled, a beam divergence ≤ 1 mrad is required. The experimental arrangement is used for obtaining a very-low-divergence beam, which is used as well for measurements of the transmission of electrons through crystals. The 22.5° dipole upstream of the dump will serve as the low energy spectrometer. The 50 MeV beam dump will be capable of absorbing up to 400 W of beam power. We expect an ultimate energy gain to be within 10 % of injection beam energy (50 MeV), which is a measurable range of the magnetic spectrometers to be installed in the ASTA beamline. Collimating the transmitted radiation to an appropriate detector will enable characterization of channeling radiation from CNT samples.

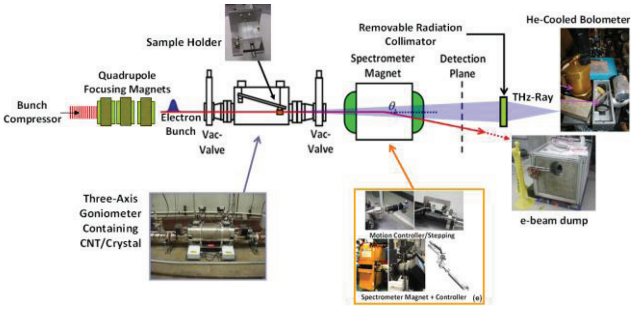

Figure 5: Outlined experimental configuration.

CONCLUSION

It seems that economic realities will impose severe constraints for the construction of a future collider beyond 2030 for under \$10B at current prices, within a footprint of 10 km, and with total electric power consumption of 10s to 100MW. The currently conceived approach based on laser-driven (x-ray) or beam-driven channeling acceleration can reach ultra high energies on the order of 100-1000 TeV within the abovementioned limits. The quest for energy will come at the price of the expected luminosities and will require at least three paradigm shifts: 1) development of new technology based on ultra-high acceleration gradients ~ 0.1 – 10 TeV/m in nanostructures; 2) acceleration of heavier particles; and 3) new approaches to physics research with luminosity limited to $\sim 10^{30\text{-}32}$ $\text{cm}^{-2}\text{s}^{-1}$. Despite the great potential of HEP colliders, excessively high driving energy and power requirements accompanied by the insufficient durability of crystal structures has removed channeling acceleration from primary consideration for high gradient (HG) accelerators. However, replacing crystals with nano-structures makes this possible by mitigating the power and energy requirements, with the advantage of improved physical strength. The fundamental mechanisms of plasmon excitation and photon-particle coupling of the nanotube can thus be studied at Fermilab-ASTA. Successful demonstration of all the simulations and experimental tests will open new opportunities for HG accelerator research efforts by merging nanotechnology and high energy physics. All of the new techniques and methods developed from heuristics will indeed be incorporated into existing technologies for current HEP collider R&D programs.

ACKNOWLEDGEMENT

We thank Alex Lumpkin for his suggestion on micro-bunching technique. We thank Philippe Piot for helpful discussion and support for the proposal and Chris Prokop for sharing his ASTA simulation design parameters.

REFERENCES

[1] W. Leemans, *ICFA Beam Dynamics Newsletter* 56 10 (2011)
[2] P. Chen, R. Noble, *AIP Conf. Proc.* 398 273 (1997)
[3] V. M. Biryukov, S. Bellucci, *Nuclear Instruments and Methods in Physics Research B* 234 (2005) 99–105
[4] V. M. Biryukov, S. Bellucci, *Nuclear Instruments and Methods in Physics Research B* 234 (2005) 99–105
[5] S. Bellucci, Nuclear Instruments and Methods in Physics Research B 234 (2005) 57–77
[6] N. Hamada, S. Sawada, A. Oshiyama, Phys. Rev. Lett. 68 (1992) 1579.
[7] Y. Saito, T. Yoshikawa, M. Okuda, N. Fujimoto, J. Phys. Chem. 54 (1993) 1849.
[8] R. Saito, M. Fujita, G. Dresselhaus, M.S. Dresselhaus, Appl. Phys. Lett. 60 (1992) 2204.\
[9] K. Tanaka, K. Okahara, M. Okada, T. Yamabe, Chem. Phys. Lett. 191 (1992) 469.
[10] Bellucci, V.M. Biryukov, Yu.A. Chesnokov, V. Guidi, W. Scandale, Nucl. Instr. and Meth. B 202 (2003) 236; V.M. Biryukov, S. Bellucci, Phys. Lett. B 542 (2002) 111.
[11] T. Tajima, and M. Cavenago, PRL 59, 1440 (1987)

[12] P. Chen and R. J. Noble, AIP. Conf. Proc. 156, 2122 (1987)

[13] http://accelconf. Web.cern.ch/accelconf/IPAC10/talks/tuoamh03_talk.pdf

[14] H. PengXiang, L. Chang, S. Chao, and C. HuiMing, Chinese Science Bulletin 57, 187 (2012)

[15] P. Muggli, V. Yakimenko, M. Babzien, E. Kallos, and K. P. Kusche, "Generation of Trains of Electron Microbunches with Adjustable Subpicosecond Spacing", PRL 101**,** 054801 (2008)