Ultimate Acceleration in Crystals and Nanostructures

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We call attention of the HEP and accelerator community to the unique opportunities offered by crystal channeling acceleration of muons [1] as well as acceleration of electrons in nanostructures. We urge for broad discussion and collaboration of the method and its studies in detail. The use of concavity of nanostructures such as CNT allows to eliminate collisions of the accelerated particles with the "background medium particles" and to serve to conduct electrons with self-focusing force. The recent invention of the Thin Film Compression technique opens the way to introduce the availability of the single-cycled laser pulse and thus the Relativistic Compressed X-ray laser pulse, which fits the need for X-ray driven nanostructured wakefield acceleration (WFA) possibility. This technology and arrangements allow the level of accelerating gradient on the order of TeV /cm [2, 3]. Such a technique could not only useful for part of the collider approach, but also it could become a new entry to seek for a non-collider paradigm, such as the PeV exploration of the vacuum property.

We believe that acceleration of muons in structured solid media offers the much needed paradigm shift. Indeed, assessing options for "ultimate" future energy frontier collider facility with c.o.m. energies O(1000 TeV), for the same reason the circular $e+e-$ collider energies do not extend beyond the Higgs and Top factory range (~0.4 TeV), it is difficult to make circular proton-proton colliders beyond 100 TeV because of unacceptable synchrotron radiation power. It is also appreciated that even in the linear accelerators electrons and positrons become impractical above about 3 TeV due to beamstrahlung (radiation due to interaction at the IPs) and about 10 TeV due to radiation in the focusing channel (<10 TeV). This leaves only $\mu+\mu-$ or pp options for the "far future" colliders. If we further limit ourselves to affordable options and request such a flagship machine not to exceed L_f ~10 km in length, then we seek a new accelerator technology providing average gradient of >30 GeV/m. One such option: super-dense medium. One example is crystals, which excludes protons because of nuclear interactions and leaves us with muons as the particles of choice. High luminosity may not be expected for such a facility if we limit the beam power and, with necessity, the total facility site power to some affordable level of P ~100MW. Indeed, as the energy of the particles E grows, the beam current will have to go down at fixed power $I=P/E$, and, consequently, the luminosity will need to go down with energy for the expense point of view. The paradigm shift from the past collider experience when luminosity scaled as $L \sim E^2$ will need to happen in the "far future" of HEP [4].

Wakefield acceleration of muons (instead of electrons or hadrons) channeling between the planes in crystals or inside carbon nanostructures (CNT) with charge carrier density ~$10^{20\text{-}23}$ cm^{-3} holds the promise of the maximum theoretical accelerating gradients of 1-10 TeV/m allowing envisioning of a compact 1 PeV linear crystal muon collider. The choice of muons is beneficial because of small scattering on solid media electrons, absence of beamstrahlung effects at the IP, and continuous focusing while channeling in crystals, i.e., acceleration to final energy can be done in a single stage.

Muon decay becomes practically irrelevant in such very fast acceleration gradients as muon lifetime quickly grows with energy as 2.2μs ×γ. Initial luminosity analysis of such machines assumes a small number of muons per bunch *O*(1000), a small number of bunches *O*(100), high repetition rate *O*(1 MHz) and ultimately small sizes and overlap of the colliding beams *O*(1 A) [5, 6].

Another important path is nanostructures such as carbon nanotubes. This medium allows not only properly design X-ray laser pulse but also electron beam acceleration with little medium particle collisions (and stopping power). Concave cavity also helps the self-focusing of the electron beam that are accelerated. This leads to the potential of on the order of TeV/ cm accelerating gradient ("TeV on a Chip") possibility. Nanostructures help also the "confinement" of the driving pulse of X-rays or charged particle beams. Furthermore, the introduction of such ultrahigh accelerating gradient opens up a path of non-luminosity paradigm of doing extreme high-energy physics, by stacking 1000 nanofibers would lead to PeV over 10m. Recall that the gamma photon wavelength at PeV is so short that the vacuum texture may be explored by such photons. In such experiments, we do not require the luminosity and thus the equipment and power necessary may be greatly reduced over the collider construct.

Comprehensive discussions on the subject have taken place at the 2019 "Workshop on Beam Acceleration in Crystals and Nanostructures" [7] and at the ARIES ACN2020 at EPFL [8]. They are summarized in the WSP book [2] and in Ref. [9]. Refs.[10, 11] provide additional insights into the physics of crystal channeling.

Excitation of wakefields in crystals or nanostructures can be possible by either short sub-μm high density bunches of X-ray laser pulses (mentioned earlier) or charged particles by electrons [12], high-Z ions, or by pre-modulated or self-modulated very high current bunches. The concept of acceleration in the crystal or CNT medium requires extensive theoretical analysis, modeling and simulations and a proof-of-principle demonstration, e.g., at the facilities like FACET-II, FAST/IOTA, AWAKE, etc.

The focus of the current R&D activities carried out by several groups and collaborations, including EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) and ALEGRO (the Advanced Lin-Ear collider study GROup) are accumulating expertise in issues such as energy transfer efficiency, production of high quality high repetition rate beams with the various driver technologies, positron acceleration, staging, and exploration of the possibilities offered by recent advances in high peak power laser technologies (similar to how chirp pulse amplification boosted the laser wakefield acceleration technique, awarded with the 2018 Nobel Prize in Physics). A number of beam test facilities addressing these major scientific challenges are either operating, coming on-line, or in the planning phase. While recent attempts to design a collider based on laser- or beam-driven WFA make steady progress (~2 GeV/m vs. maximum single stage value of 10-50 GeV/m), we can also explore additional new avenue of breakthrough technologies of high-energy physics.

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