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APPLICATION OF NANOSTRUCTURES AND METAMATERIALS IN ACCELERATOR PHYSICS*

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Abstract

Carbon-based nanostructures and metamaterials offer extraordinary mechanical and opto-electrical properties, which make them suitable for applications in diverse fields, including, for example, bioscience, energy technology and quantum computing. In the latest years, important R&D efforts have been made to investigate the potential use of graphene and carbon-nanotube (CNT) based structures to manipulate and accelerate particle beams. In particular, the interaction of graphene and CNTs with charged particles and electromagnetic radiation might open interesting possibilities for the design of compact coherent radiation sources, and novel beam diagnostics techniques as well. This paper gives an overview of novel concepts based on nanostructures and metamaterials with potential application in the field of accelerator physics. Several examples are shown and future prospects discussed.

INTRODUCTION

Since their discovery, carbon nanotubes (CNTs) [1] and graphene [2] have found countless applications in multiple fields, e.g. electronics, photonics, bioscience, energy technology, etc. Therefore, it is worth asking about the potential of the use of graphene and carbon nanotechnology in the field of accelerator physics. Due to their special optoelectronic, thermal and mechanical properties, CNT and graphene based structures might offer novel and alternative solutions to overcome many of the present limitations of several accelerator subsystems, thus enhancing the capabilities of future accelerators. For instance, they might open new paths for manipulation and acceleration of beam particles beyond the current state-of-the-art.

In this paper we discuss potential applications of carbon based nanostructures and metamaterials in particle accelerator physics. Concretely, we give representative examples for solid-state wakefield acceleration, electron guns and beam diagnostics.

SOLID-STATE BASED ACCELERATION

In the field of accelerator physics, the channeling properties of silicon crystal have successfully been used for collimation and extraction of relativistic proton beams [3]. Solids can also provide an alternative medium for acceleration. Depending on their particular atomic configuration and electrical conduction nature, some solid-state micro- and nano-sized structures offer interesting properties to enhance electric field components or induce strong wakefields that could be useful for acceleration, as well as transverse particle guiding and radiation emission.

Semiconductor and metallic crystalline lattices have been proposed to generate a solid-state plasma medium to guide and accelerate charged particles, taking advantage of the channelling properties in crystals. High electron density in solids could be obtained from the conduction bands. Typical electron densities (n_e) in solid-state plasmas lie within the range of 10^{19} cm^{-3} $\leq n_e \leq 10^{24}$ cm^{-3} [4, 5], i.e. between one and six orders of magnitude higher than the density in gaseous plasmas. Taking into account that the maximum accelerating field depends on the electron density as $E_z[\text{V/m}] \approx 96\sqrt{n_e[\text{cm}^{-3}]}$, solid-state based plasmas might lead to accelerating gradients 0.1 TV/m $\lesssim E_z \lesssim$ 100 TV/m.

Solid-state wakefield acceleration using crystals was proposed in the 1980s and 1990s by T. Tajima and others [4,6,7] as a technique to sustain TV/m acceleration gradients.

Wakefields in crystals can be induced by means of the excitation of high-frequency collective motion of conduction electrons through the crystalline lattice. To reach accelerating gradients on the order of ~TV/m, crystals must be excited by ultrashort X-ray laser pulses within a power range of TW– PW, which makes the practical realisation of the concept very challenging. It has only recently become a realistic possibility since the invention of the so-called single-cycled optical laser compression technique by G. Mourou et al. [8].

If natural crystals (e.g. silicon) are used for solid-state wakefield acceleration, the beam intensity acceptance is significantly limited by the angstrom-size channels. In addition, such small size channels increase the dechanneling rate and make the channels physically vulnerable to high energy interactions, thus increasing the damage probability by high power beams.

Over the past decade there have been great advances in nanofabrication techniques [9] that could offer an excellent way to overcome many of the limitations of natural crystals. Metallic nanostructures and metamaterials [10, 11] could lead to suitable ultra-dense plasma media for wakefield acceleration or charged particle beam manipulation, i.e. channelling, bending, wiggling, etc. This also includes the

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possibility of investigating new paths towards ultra-compact X-ray sources [10]. The possibility to excite high acceleration gradients in multilayer graphene structures is also being investigated [12].

Plasmonic Wakefield Acceleration

Plasmonics can be defined as the study of the interaction between electromagnetic fields and the free electron Fermi gas in conducting solids. External electromagnetic fields can excite plasmons, i. e. collective oscillations of conduction electrons in metals [13]. To some extent, this collective effect could be exploited to generate ultra-high acceleration gradients. Figure 1 depicts a scheme of excited plasmons in metallic surfaces. The oscillation of induced longitudinal electric field reminds that in a sequence of a multi-cell RF cavity operating at π-mode.

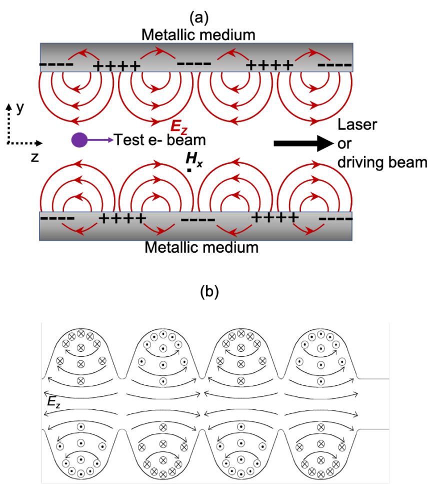

Figure 1: (a) Plasmonic acceleration concept. (b) Comparison with a RF cavity operating in π-mode. The drawings are not to scale. While the plasmonic structure has micrometric or submicrometric apertures and length on the order of 1 mm, for instance a 9-cell RF cavity has usually apertures of tens of mm and length on the order of m.

The excitation of surface plasmonic modes [14, 15] can be driven either by charged particle beam [16] or by laser [17]. To be effective, the driver dimensions should match the spatial (~ nm) and time (sub-femtoseconds) scales of the excited plasmonic oscillations. Wakefield driving sources working on these scales are now experimentally realizable. For instance, attosecond X-ray lasers are possible thanks to the pulse compression technique [8]. In the case of beam-driven wakefields, the experimental facility FACET-II at SLAC [18] will allow the access to “quasi-solid” electron bunches with densities up to 10^{24} cm^{-3} and submicron longitudinal size. A comparison of the range of spatial and time scales of the electric field oscillations and achievable acceleration gradient for standard and novel acceleration methods is shown in Fig. 2. In principle, solid-state wakefields and plasmonics acceleration with nanostructures are predicted to have the potential to generate higher acceleration gradients than Dielectric Wakefield Acceleration (DWA) [19] and Dielectric Laser Acceleration (DLA) [20], Laser Wakefield Acceleration (LWFA) [21] and Plasma Wakefield Acceleration (PWFA) [22] with gaseous plasma.

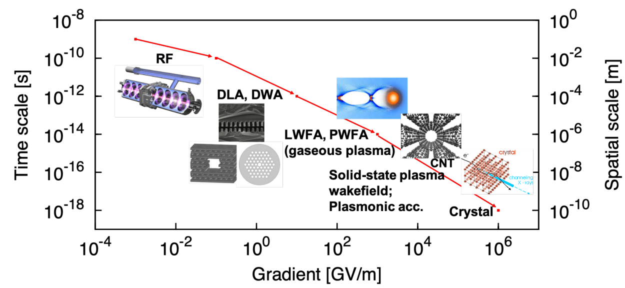

Figure 2: Schematic comparing the space and time scales of the longitudinal electric field components generated by different techniques for charged particle acceleration and their corresponding amplitude (acceleration gradient). The cases of nanostructure wakefields, plasmonic and crystal acceleration are based on theoretical and numerical predictions.

Due to their special thermo-mechanical and optoelectronic properties, materials based on carbon nanotubes arrays or graphene could be an excellent medium to generate plasmonic wakefield acceleration. In principle, such as proved in [23], in the linear regime the plasmonic dynamics in CNT bundles can be described by classical plasma formulae.

Particle-In-Cell (PIC) simulations of beam driven wakefield acceleration in cylindrical metallic hollow structures (Fig. 3) with micrometric or nanometric apertures have shown the feasibility of obtaining gradients $\gtrsim$ 100 GV/m, envisioning the possibility of an ultra-compact PeV linear collider [24–26]. Similar gradient values have also been predicted from PIC simulations of X-ray laser driven wakefield acceleration in nanotubes [27].

ELECTRON FIELD EMITTERS

2D nanomaterials can have greatly enhanced electron field emission properties that are interesting to be applied to cathodes and injectors in accelerator facilities. For instance, it has been experimentally observed that certain configurations of CNT arrays could permit to extract relatively high-current densities of cold electrons (~ 1–10 mA/cm^2) at a relatively low-applied electric field (~ V/μm), with relatively high stability and lifetime [29, 30]. Figure 4 shows the image of a honeycomb-like CNT array and its current density emission as a function of time. These configurations of CNT arrays have great potential as cold electron field emitters, and are expecting to produce electron beams with transverse energy spread < 100 meV and longitudinal energy spread ~ 1 meV. CNT based cold electron field emitters can be applied to the electron gun of electron coolers of low energy antimatter facilities, such as the ELENA (Extra-Low ENergy Antipro-

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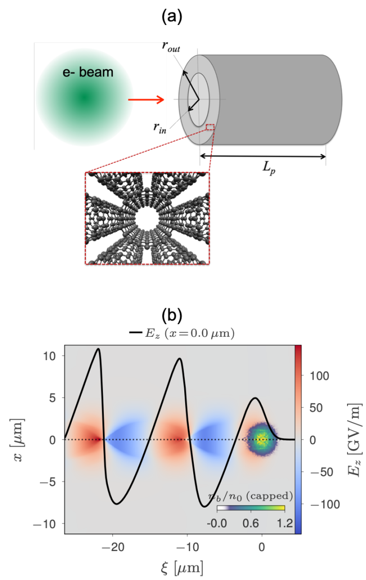

Figure 3: (a) Schematic model for beam-driven wakefield simulation using a hollow cylinder of solid-state plasma confined in a wall of thickness $r_{out} - r_{in}$ and length L_p. In this model the cylinder wall represents a solid made of CNT bundles. (b) An example of longitudinal wakefield as a function of the comoving coordinate $\xi = z - ct$, with c the speed of light. This particular case has been computed using the PIC code FBPIC [28].

ton) ring at CERN [31]. The use of a CNT based electron gun in the ELENA cooler, aside from hopefully decreasing the electron beam temperature, would also allow simplification of the gun arrangement, eliminating the necessity of a heating filament, thus making the conditioning process faster and simpler, while at the same time achieving a more efficient electron cooling process.

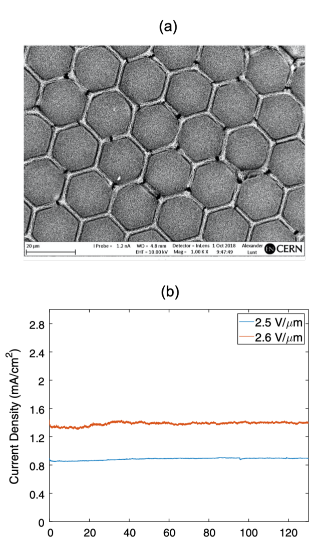

Figure 4: (a) SEM image of a honeycomb-like CNT array. (b) Emission stability test for a honeycomb-like CNT array at two different applied electric fields.

BEAM DIAGNOSTICS

Projects like the High Luminosity LHC [32] and the Future Circular Collider (FCC) [33, 34] aim to obtain higher beam intensity, higher beam energy and smaller beam sizes. Therefore, to measure the transverse density profile robust and optimised wire-scanners will be required. Recent studies have shown that CNT wiring can be a good candidate, combining low density, low atomic number, high tensile strength (> 100 GPa for single wall CNTs) and high temperature resistance (melting temperature ~3000 – 4000 K) [35].

Another interesting application is the generation of terahertz Smith-Purcell radiation induced by surface plasmonics excited by electrons moving parallel to graphene metasurfaces or nanoscale gratings, which can be used for temporal characterisation of ultrashort electron pulses with durations < 100 fs [36, 37].

CONCLUSIONS AND OUTLOOK

Nanostructures and metamaterials based on CNTs and graphene, due to their special and flexible optoelectronic, thermal and mechanical properties, could find interesting applications in the field of accelerator physics, solving some of the limitations posed by standard technologies. They could also offer novel pathways to access multi-GV/m and multi-TV/m field regimes towards more sustainable, compact and low-cost accelerating methods. In addition, they could be an excellent and robust medium to design novel electron guns, beam diagnostics and compact radiation sources.

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