Towards High-gradient Particle Accelerators from Carbon Nanotube Arrays

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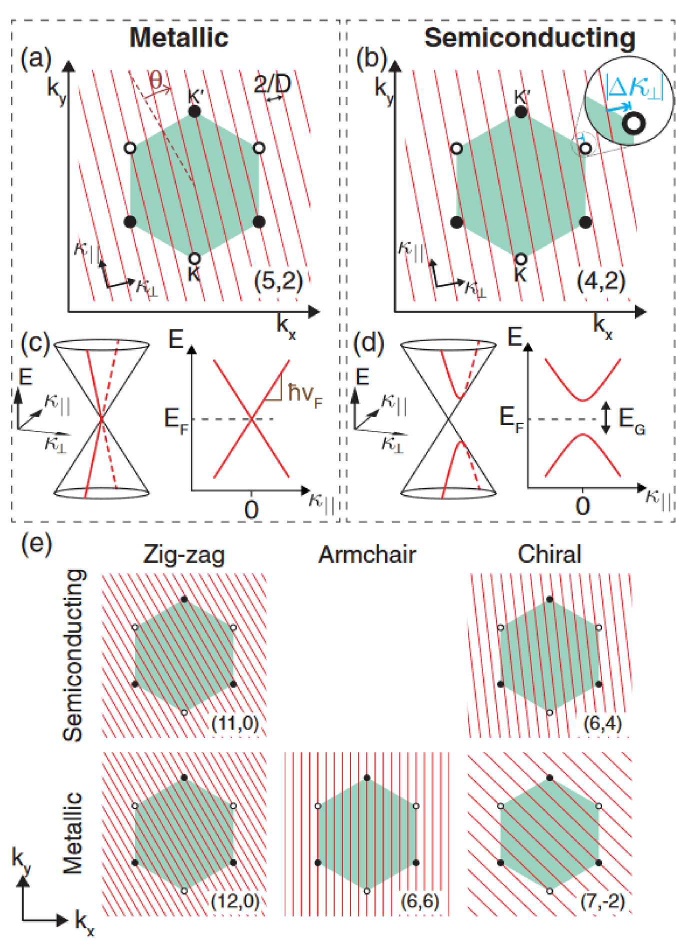
Abstract

Charged particle acceleration using solid-state nanostructures is attracting new attention in recent years as a method of achieving ultra-high acceleration gradients, in principle of up to ~1 TV/m [1]. The use of carbon nanotubes (CNT) has the potential to enable limitations of using natural crystals, e.g. in channeling aperture and thermo-mechanical robustness, to be overcome.

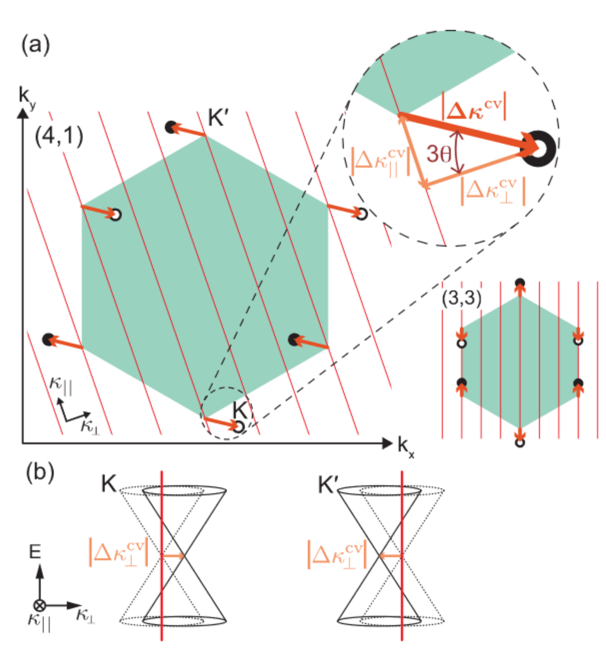
Here we present preliminary results of ongoing work in the development of a new, quasi-3D simulations of electrons in unionized multiwall carbon nanotubes using modification to the particle-in-cell code *EPOCH* [2].

1. Effective thick-shell model for MWNTs

1. Metallic CNT with mobile electrons requires Fermi Surface within occupied band

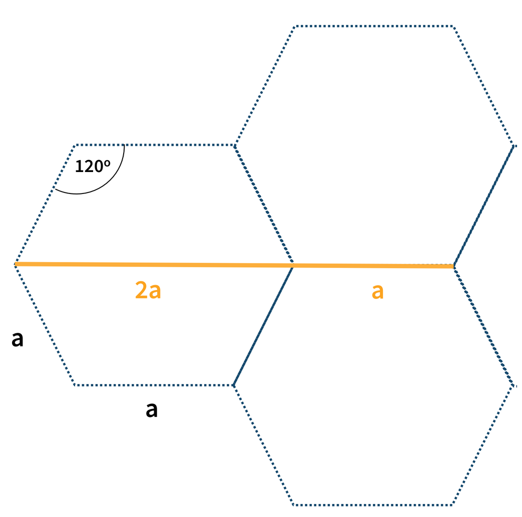


2. Curvature of graphene sheet into CNT gives extra constraint: only armchair CNTs are truly metallic

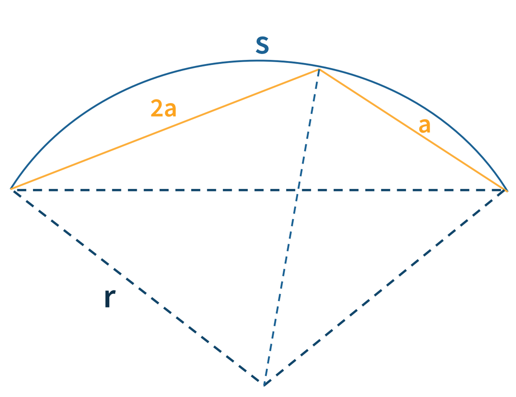


Laird, EA et al. 2015 *Quantum transport in carbon nanotubes* Rev. Mod. Phys. **87** *http://dx.doi.org/10.1103/RevModPhys.87.703*

3. Assume C-C bonds retain length from graphene:



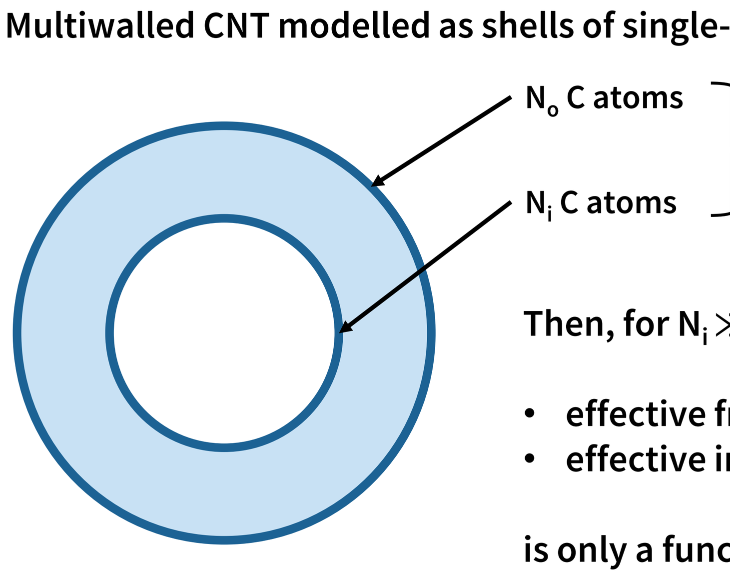
4. CNT radius can be calculated as function of number of Carbon atoms, *N*, in circumference of bounding circle



$$r(N) = \frac{\sqrt{9a^2 - 4a^2\left(1 - \cos\left(\frac{2\pi}{N}\right)\right)}}{2\sin\left(\frac{2\pi}{N}\right)}$$

$$r(N) \approx \frac{3aN}{2\pi} \quad \text{for} \quad N \gg 4$$

5. Multiwalled CNT modelled as shells of single-walled CNTs



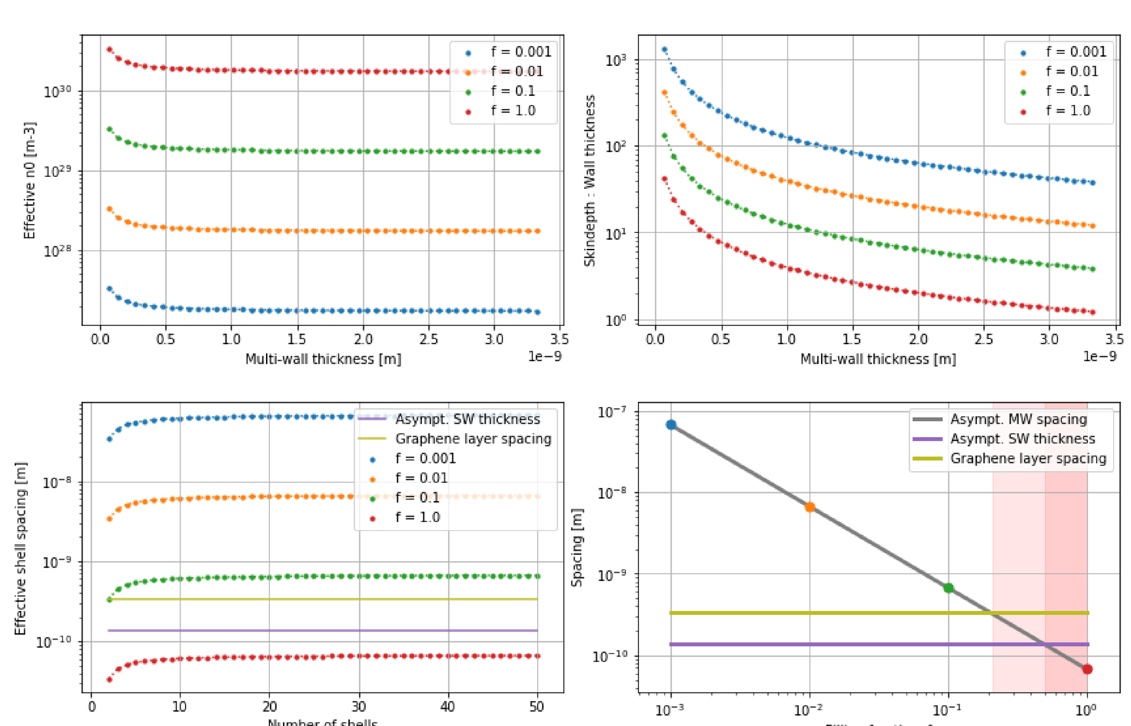
a) $N_s = 1+(N_o - N_i)/2$ possible shells in-between
b) Only fraction *f* of possible shells present
c) CNT has f x N_s walls

Then, for $N_i \gg 4$ (r > 2 nm) and $(N_o - N_i) \gg 1$

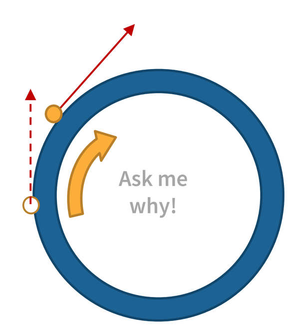
- effective free-electron number density
- effective inter-wall spacing

is only a function of total thickness and filling fraction, *f*

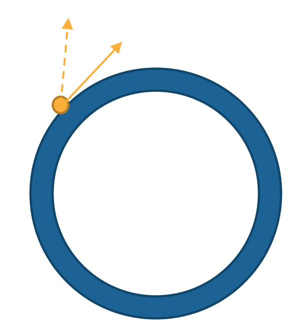
6. Asymptotically, can find effective density and shell spacing, parameterised by a single 'filling fraction'



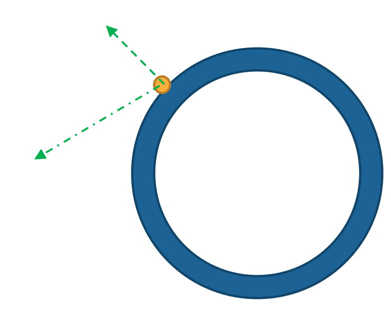
2. Boris push on cylindrical surface



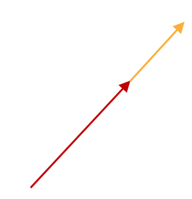
1. Drift-rotate particle to Time where E, B is defined.



2. Project E to azimuth

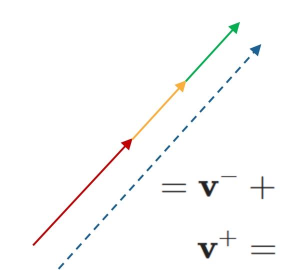


3. Project torque pseudo-vector to radial direction



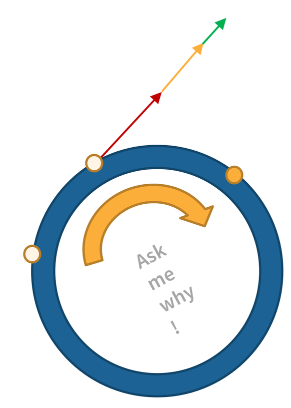
$$\mathbf{v}^{n-1/2} = \mathbf{v}^- - \frac{q\mathbf{E}}{m}\frac{\Delta t}{2}$$

4. Half-accelerate previous velocity using E

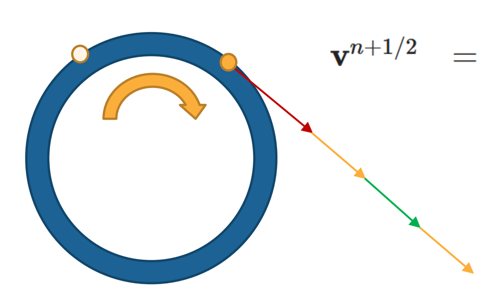


$$= \mathbf{v}^- + \mathbf{v}' \times \mathbf{s}$$
$$\mathbf{v}^+ = \mathbf{v}^- + \mathbf{v}' \times \mathbf{s}$$

5. Apply torque (only z and φ change to velocity)

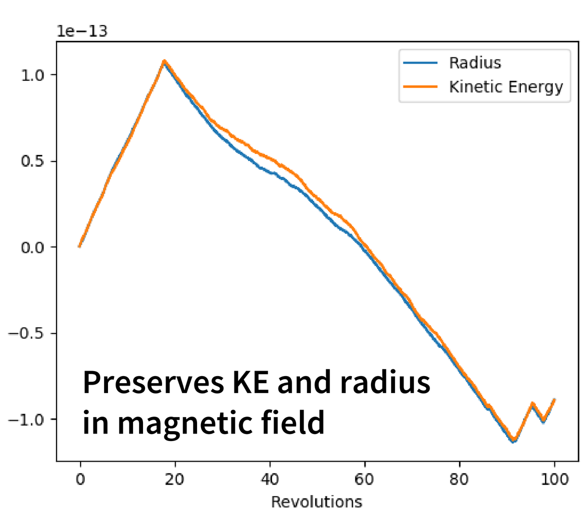


6. Rotate particle from initial position using velocity at rotation midpoint

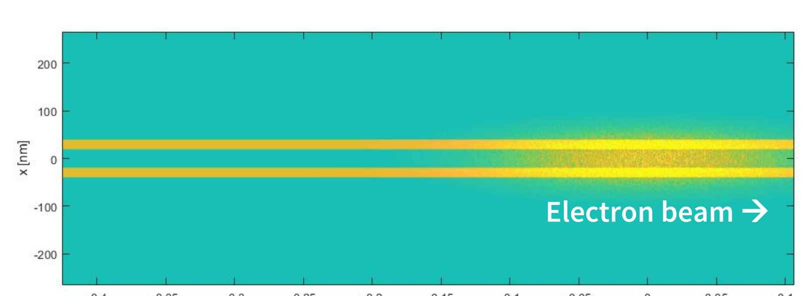


$$\mathbf{v}^{n+1/2} = \mathbf{v}^+ + \frac{q\mathbf{E}}{m}\frac{\Delta t}{2}$$

7. Apply remaining acceleration and rotate velocity to new particle position

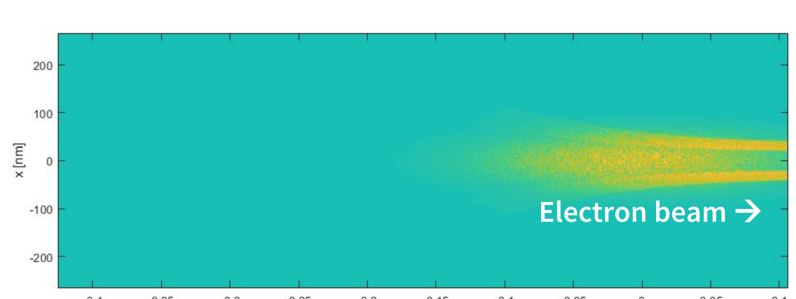


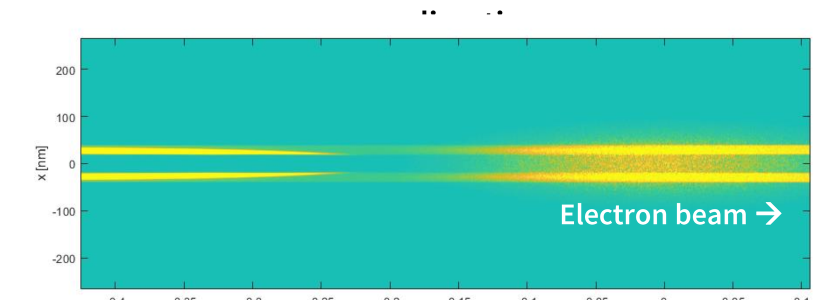
3. Preliminary EPOCH simulations



Isotropically free current

Force zero wall electron acceleration in radial direction





- We use modified 3D *EPOCH* [2] code to model nanotube wall electrons as plasma in a static positive 'jellium' background
- Electron motion in walls restricted to longitudinal and azimuthal directions

4. Ongoing work

- Extension of rigid-wall single-nanotube model to full CNT array
- In-depth study of array field and plasmon modes
- Development of a theoretical framework for EM fields and operation of CNT-array in coupled operation (most likely to be used with existing beamlines)

[1] Shin, Y. M. (2017). Ultra-high gradient channeling acceleration in nanostructures: Design/progress of proof-of-concept (POC) experiments. AIP Conference Proceedings , 1812(060009). doi: 10.1063/1.4975876 .

[2] Arber, T. D. (2015). Contemporary particle-in-cell approach to laser-plasma modelling. Plasma Physics and Controlled Fusion, 57(11), 113001. doi: 10.1088/0741-3335/57/11/113001

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Work supported by Science and Technology Facilities Council grant ST/P006752/1.