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, 3D model of beam-CNT and beam-CNT-array interaction using modification to the particle-in-cell code EPOCH [2].

1. Proposed Setup

- High density of CNT wall leads to ultra short-wavelength (~100nm) accelerating fields
- Bunch compressor chicane for ~0.1 ps bunches (multiple wavelengths)
- Even shorter bunches at sub-fs level from bunch slicing in magnetic chicane with a collimator

2. 2D Particle-in-cell Simulations

- CNT array modelled as multi-hollow plasma in PIC code EPOCH [2]
- With high-density \( n_B - n_{CNT} \) beam, up to 10s of GeV/m ... but ‘nanotubes’ bend in simulation

3. New 3D rigid-wall CNT model

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

4. Expt. Proof-of-Concept Possibilities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CLEAR (CERN)</th>
<th>CLARA (DL)</th>
<th>EuPRAXIA*</th>
<th>EuPRAXIA, LWFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>200 MeV</td>
<td>250 MeV</td>
<td>150 MeV</td>
<td>400-1250 MeV</td>
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<tr>
<td>Energy spread</td>
<td>&lt; 2%</td>
<td>±1%</td>
<td>0.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Trans. norm. emittance (rms)</td>
<td>&lt; 20 mm-mrad</td>
<td>1-3 mm-mrad</td>
<td>1 mm-mrad (proj.)</td>
<td></td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>&lt; 0.75 ps</td>
<td>0.1-0.25 ps (short pulse)</td>
<td>1 um (0.003 ps)</td>
<td>50-6000 fs</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.6 nC</td>
<td>0.1-0.25 nC</td>
<td>0.03 nC</td>
<td>50-800 pC</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>0.667 ns</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Nb. of bunches</td>
<td>1-32-226</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>[0.5, 5] Hz</td>
<td>10 Hz</td>
<td>1-10 Hz (macro)</td>
<td>0.04-3 MHz (micro)</td>
</tr>
</tbody>
</table>


5. Ongoing work

- Further investigation and extension of rigid-wall single-nanotube model to full CNT array
- Addition of CNT-electron scattering and other solid-state effects
- Development of a theoretical framework for EM fields and operation of CNT-array in coupled linear regime (most likely to be used with existing beamlines)
- Optimization studies of wall-thickness, nanotube radius, crystalline geometry and array properties