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.

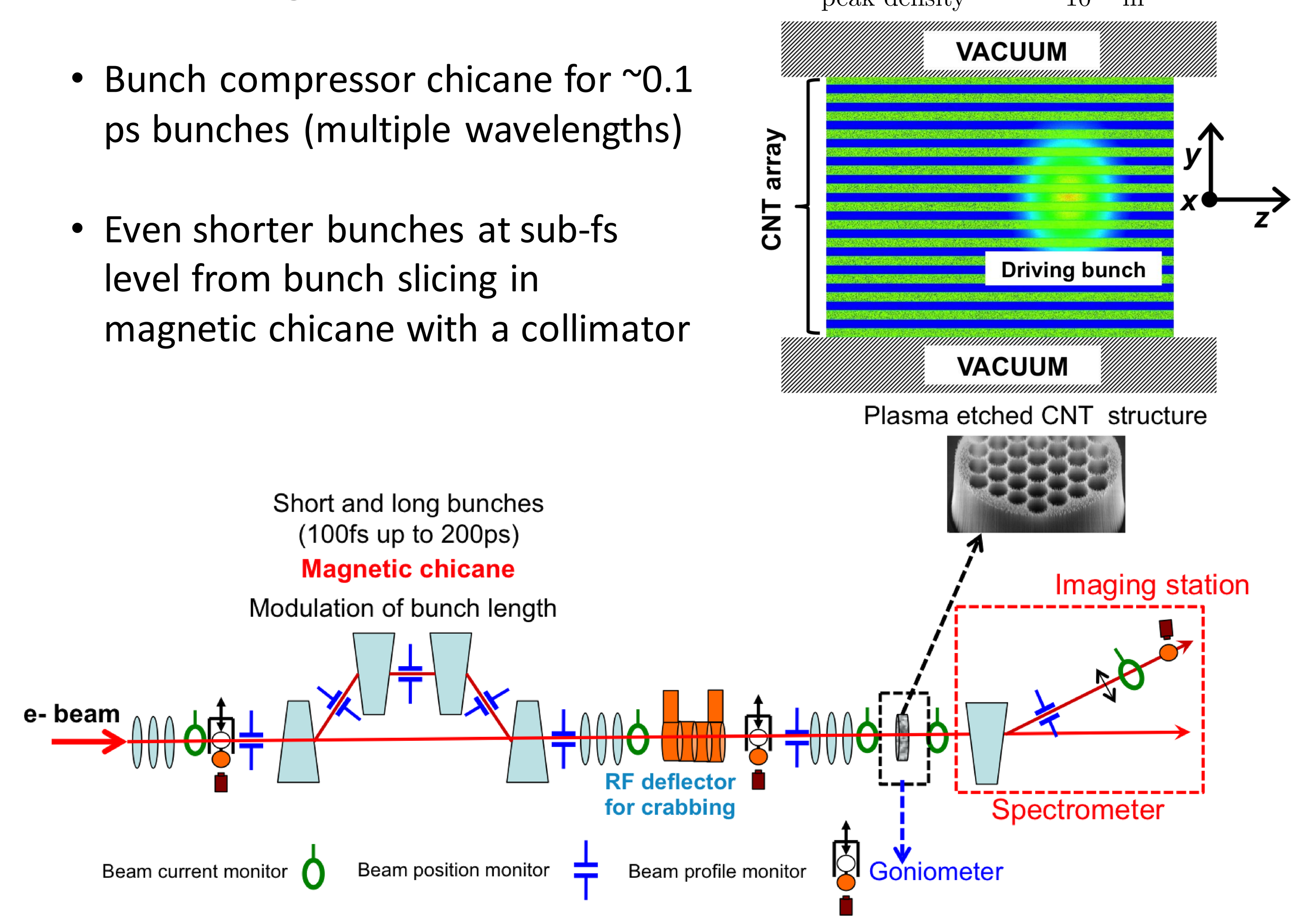
Here we present preliminary results of ongoing work in the development of a new, 3D model of beam-CNT and beam-CNT-array interaction using modification to the particle-in-cell code *EPOCH* [2].

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

Typical bunch parameters

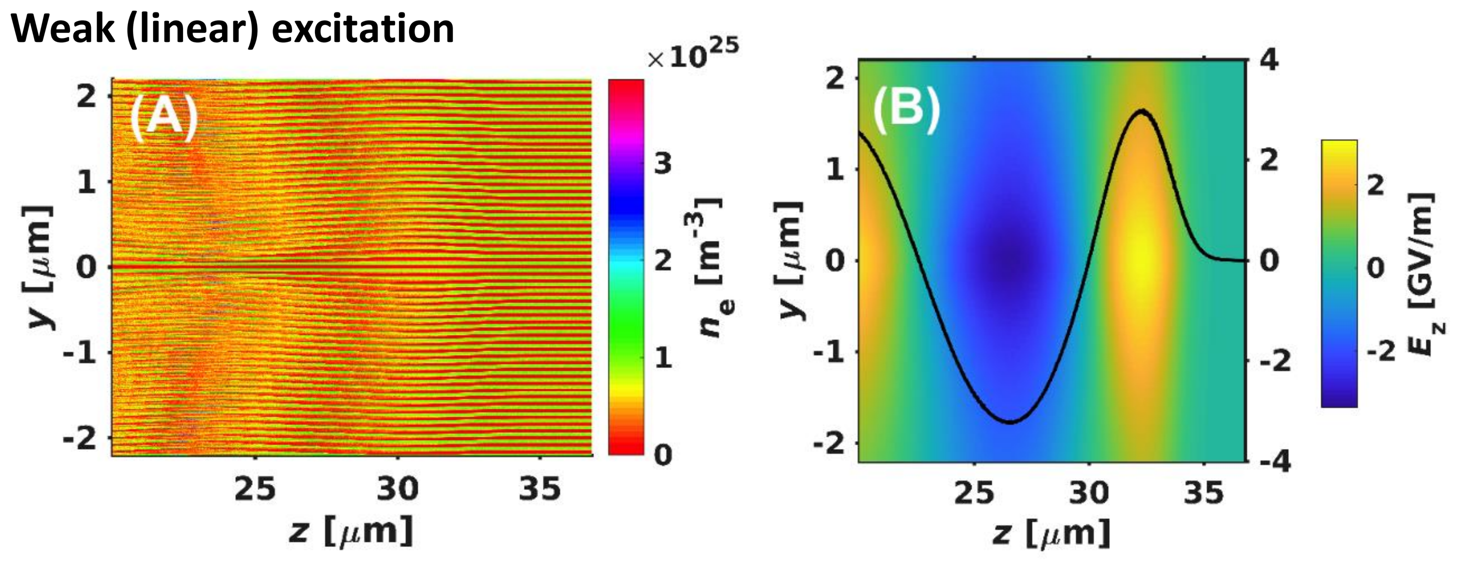
Energy	200 MeV
Energy spread	1%
Bunch population	5×10^6
rms radius	$168(0.1c/\omega_p)$ nm
rms length	$840(0.5c/\omega_p)$ nm
peak density	10^{25} m^{-3}



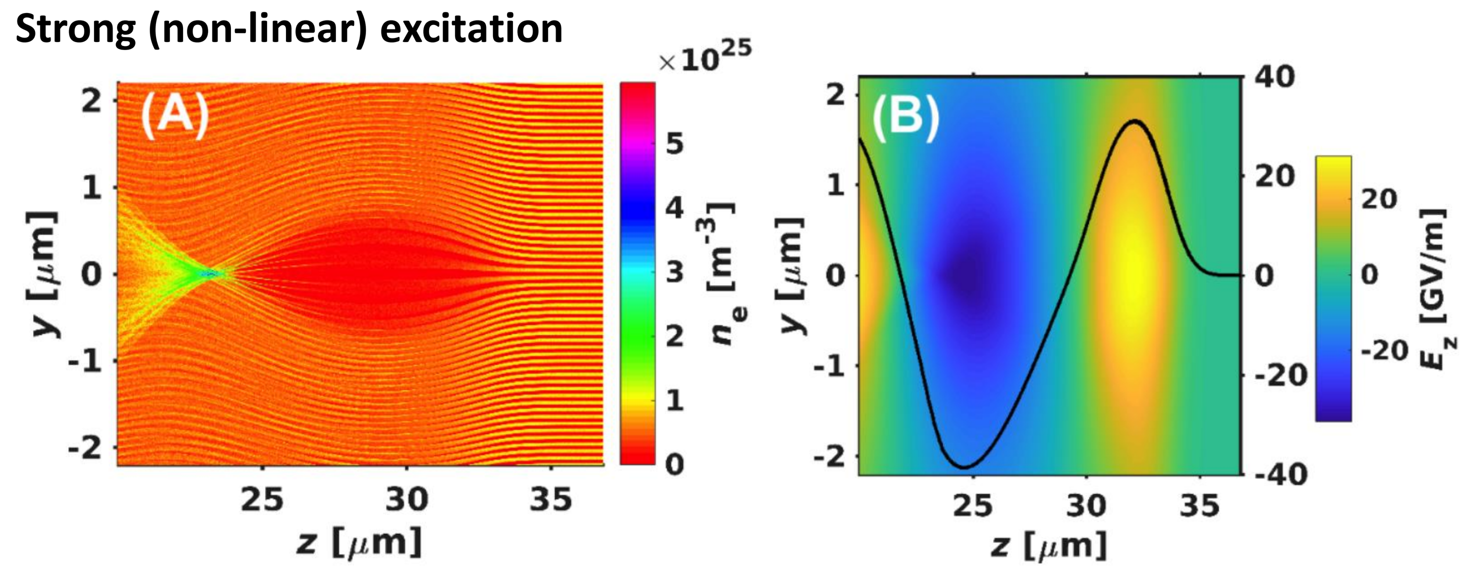
2. 2D Particle-in-cell Simulations

- CNT array modelled as **multi-hollow plasma** in PIC code *EPOCH [2]*
- With high-density ($n_b \sim n_{CNT}$ beam, up to **10s of GeV/m** …
  … but 'nanotubes' **bend** in simulation

Weak (linear) excitation



Strong (non-linear) excitation



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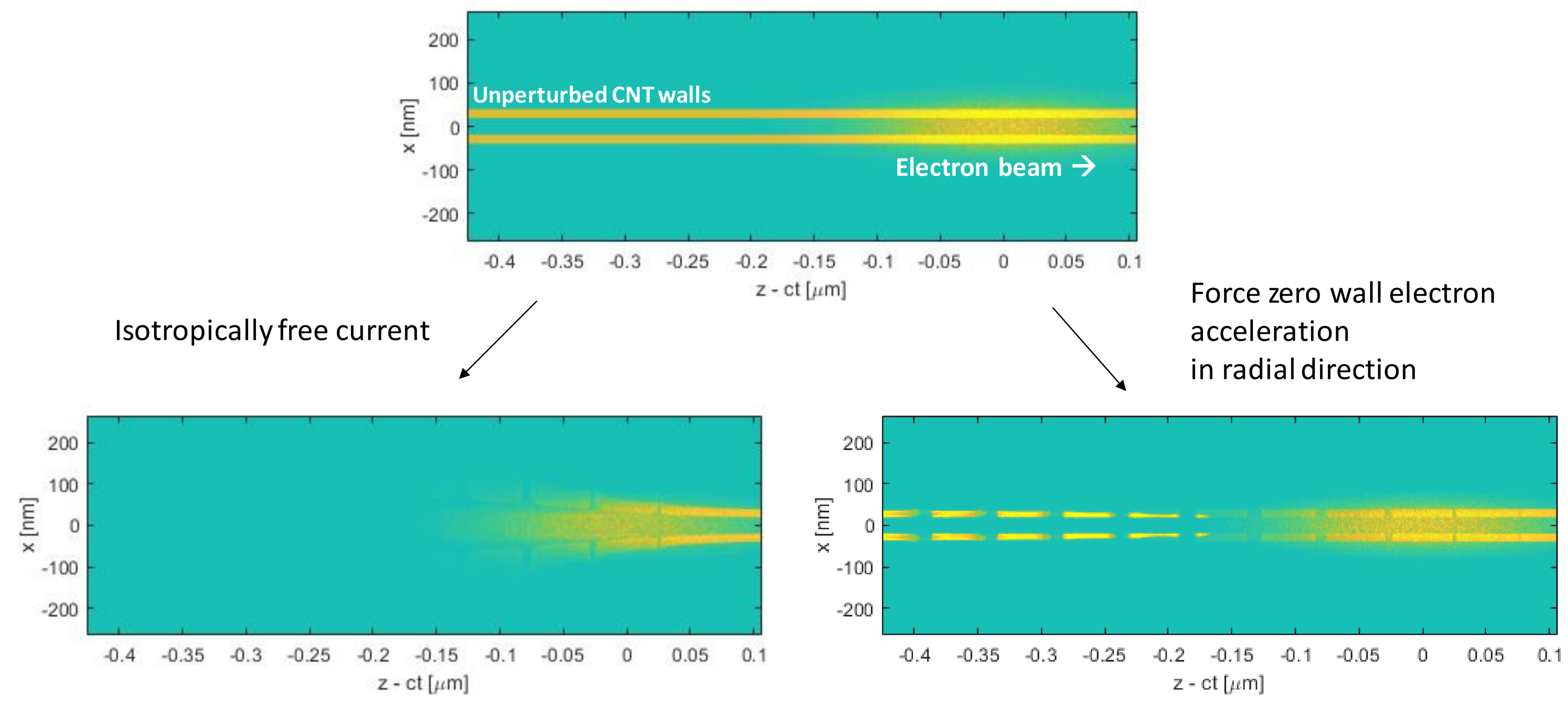
3. New 3D rigid-wall CNT model



- 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

Parameter	CLEAR (CERN)	CLARA (DL)	EuPRAXIA*	EuPRAXIA, LWFA
Energy	200 MeV	250 MeV	150 MeV	400-1250 MeV
Energy spread	< ±2%	±1%	0.5%	0.02%
Trans. norm. emittance (rms)	< 20 mm-mrad	≤ 1 mm-mrad	1 mm mrad	1-3 mm mrad (proj.)
Bunch length (rms)	< 0.75 ps	0.1-0.25 ps (short pulse)	1 um (0.0033 ps)	50-6000 fs
Bunch charge	0.6 nC	0.1-0.25 nC	0.03 nC	50-800 pC
Bunch spacing	0.667 ns	--	-	-
Nb. of bunches	1-32-226	1	-	-
Repetition rate	[0.8, 5] Hz	10 Hz	-	1-10 Hz (macro) 0.04-3 MHz (micro)

*P. A. Walker et al., Horizon 2020 eupraxia design study, J. Phys. Conf. Ser. 874 (confer) (2017)

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

[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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