The Cockcroft Institute
of Accelerator Science and Technology

Studies of ultra-high gradient acceleration in carbon nanotube arrays

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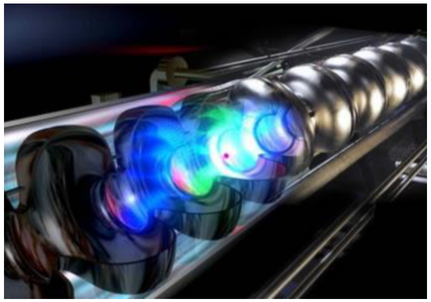
The University of Liverpool and Cockcroft Institute

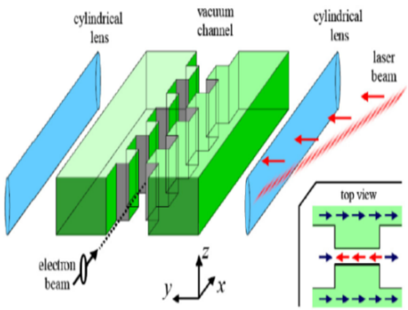
Outline

- Introduction
- State-of-the-art
- Simulation models
- Experimental layout
- Summary and perspective
- Future plan

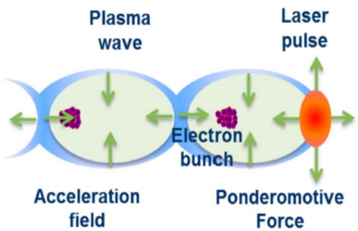
Introduction



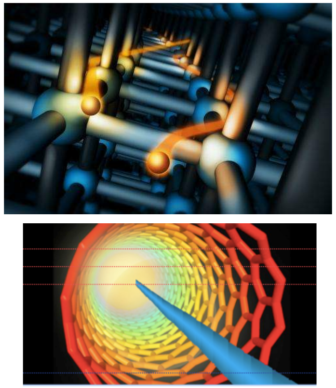
Tesla cavity in DESY



DLA



PWFA

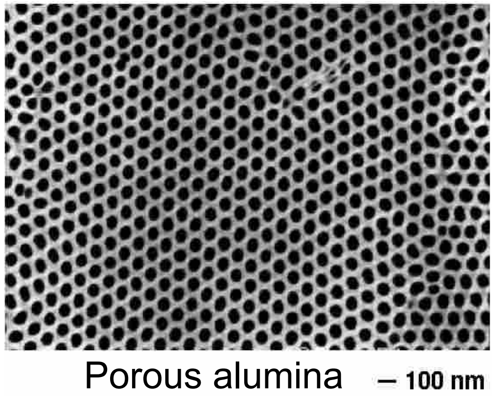


ACN

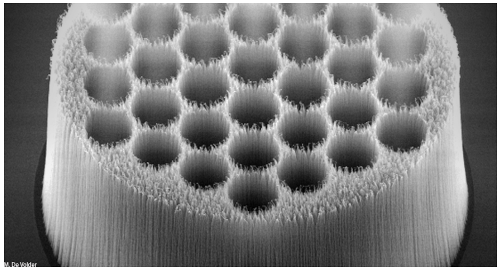
	Conventional RF cavity	Dielectric laser – driven acceleration (DLA)	Plasma wakefield acceleration (PWFA)	Solid–state plasma wakefield acceleration
Based on	Normal / superconducting cavity	Quartz / silicon structure	Gaseous plasma	Crystals, e.g. Silicon / nano-channels, e.g. CNT
Peak field limited by	Surface breakdown	Damage threshold	Wave breaking	Atomic lattice dissociation
Maximum achievable gradient	50 – 100 MV/m	~10 GV/m	~100 GV/m	~1 – 100 TV/m (prediction)

Using nanostructures

- Wakefield acceleration in porous nanomaterials
- Advantages of CNT w.r.t. natural crystals:
  - Higher acceptance: CNT channel size ~(1-100) nm; channel size for Si crystal ~ Å
  - Lower dechannelling rate
  - Lower stopping power
  - Significantly higher thermal and mechanical robustness
  - Great degree of dimensional flexibility
- Wakefield drivers:
  - Beam
  - High power laser



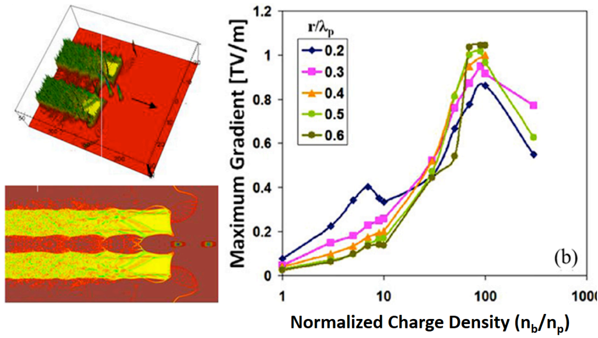
Porous alumina



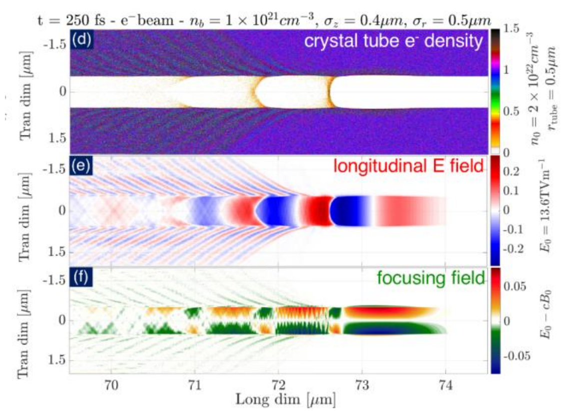
CNT array
Michael De Volder et al., Uni. of Cambridge

State-of-the-art. Simulations

- Beam-driven WA in a single CNT channel



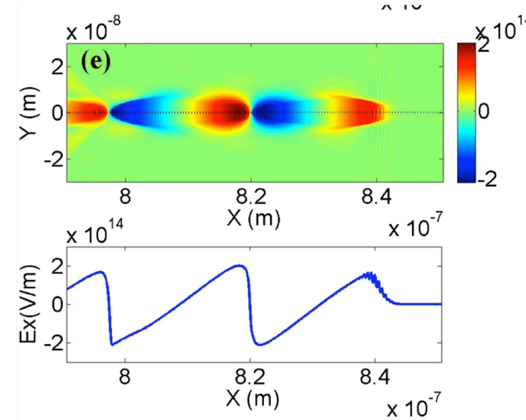
Y. M. Shin et al., AIP Conf. Proc. 1812 (2017) 060009



A. Sahai et al., IJMP **34** (2019) 1943009

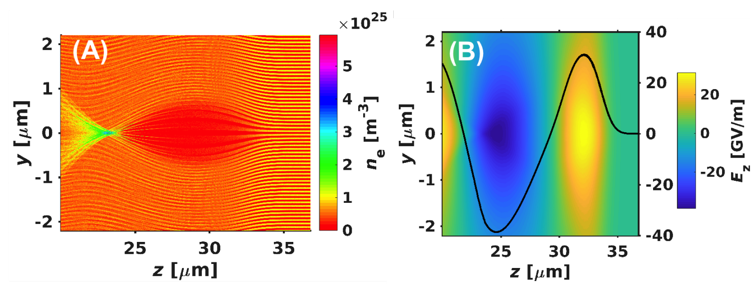
e-beam

- LWA in a single CNT channel



X. Zhang et al., PRST-AB **19** (2016) 101004

- Beam-driven WA in CNT arrays

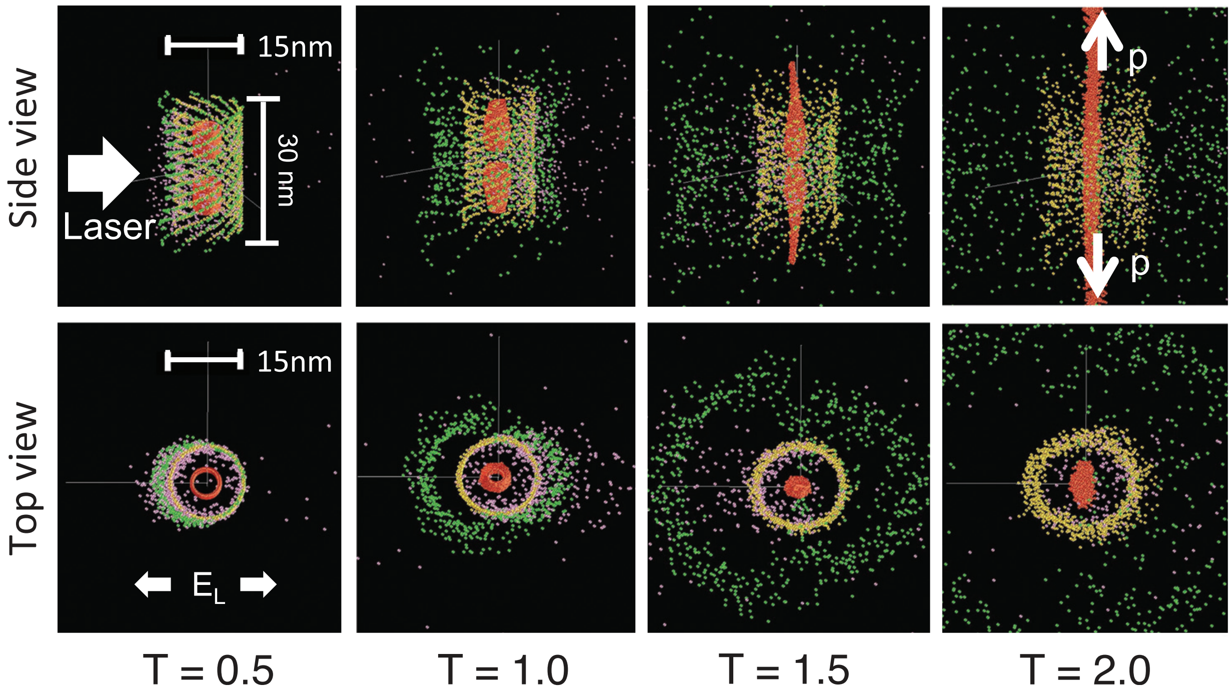


J. Resta-Lopez et al., IPAC2018

Prediction of 100-GV/m to TV/m fields

State-of-the-art. Simulations

- Intense-laser driven nanotube based proton beam accelerator



M. Murakami, M. Tanaka., Appl. Phys. Lett. 102 (2013) 163101

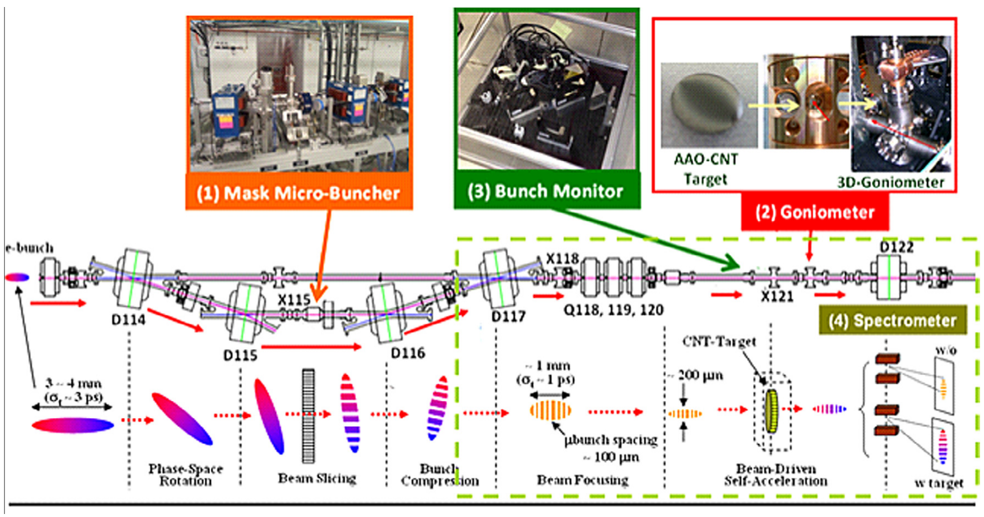
- Laser: 10-20 fs; I=10^{18} W cm^{-2}
- Outer CNT (green) with Au atoms (yellow) chemically adsorbed
- Two inner bullet nanotubes made of H (red)
- Ionized electrons (white) are ejected
- A saddle-shaped Coulomb field is generated to squeeze and accelerate the bullet ions along the z-axis

Prediction of 100 TV/m fields

State-of-the-art. Exp. proposals

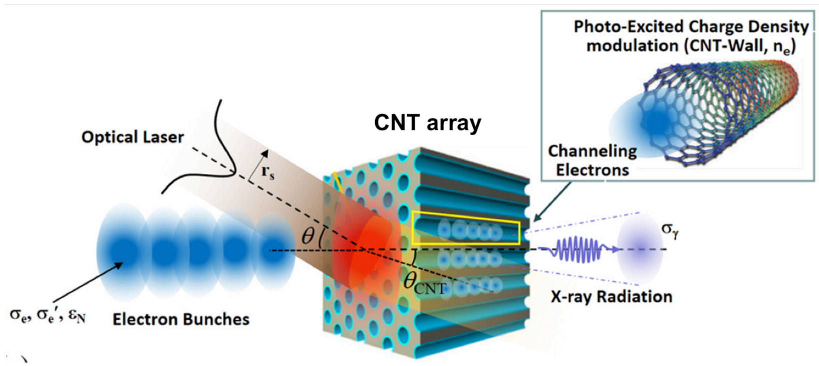
- Earlier experimental proposals

ASTA 50 MeV beamline @ Fermilab



Y. M. Shin et al.

- Coherent X-ray radiation from photo-excited CNT



Simulation studies

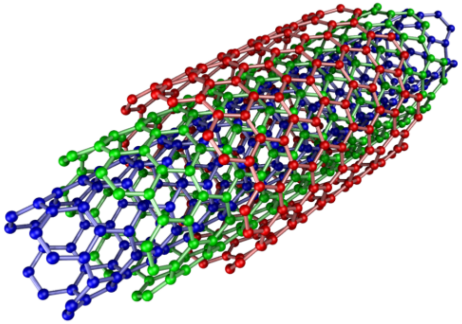
- What do we want to simulate?

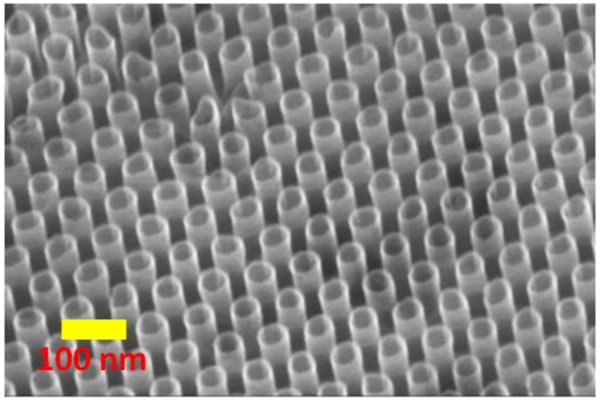
  – Single- and multi-walled CNTs

    • Free electrons (ionised by laser or strong beam fields)

    • Quasi-free electrons (2D Fermi gas)

  – Array of many such coupled CNTs suitable for channelling wide (micron-scale) beams





2D hollow plasma PIC simulations

- Single channel model. Beam-driven.
  - Beam and CNT dimensions: parametrised as a function of λ_p .

e-beam:

$\sigma_z = 0.1\,\lambda_p$

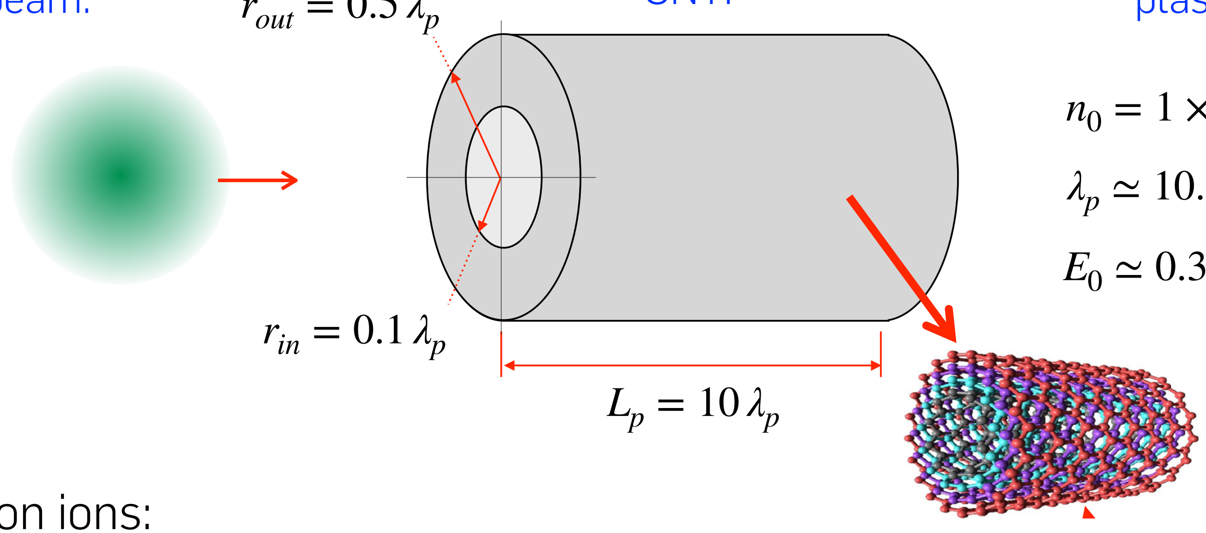
$\sigma_r = 0.1\,\lambda_p$

$E_{k0} = 1\,\text{GeV}$

$Q_b = 33\,\text{pC}$

$n_b/n_0 = 1.1$

CNT:



plasma:

$n_0 = 1 \times 10^{25}\,\text{m}^{-3}$

$\lambda_p \simeq 10.6\,\mu\text{m}$

$E_0 \simeq 0.3\,\text{TV/m}$

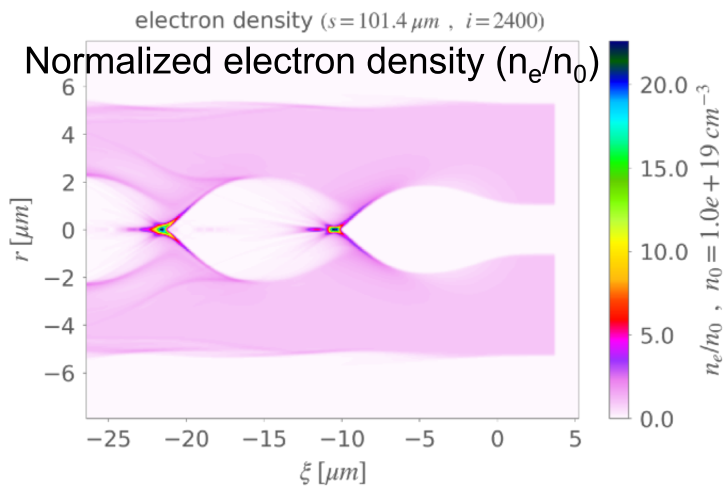
- Carbon ions:
  - $q = e$ (single-level ionisation);
  - $m_C \simeq 12\,m_p$;

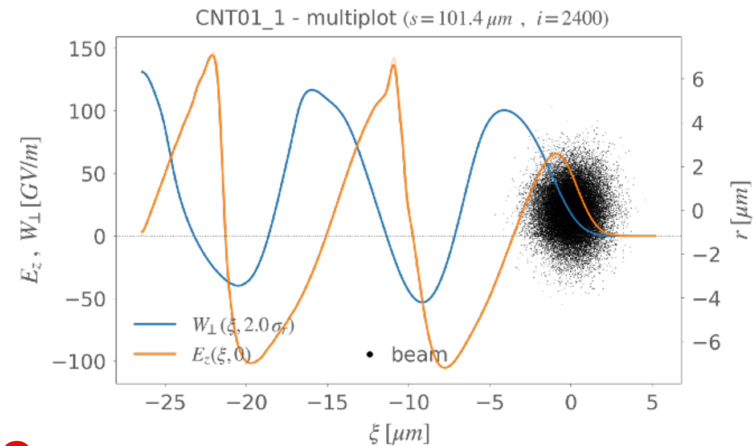
2D axisymmetric
Free electron gas on CNT wall

[See A. Bonatto presentation.This workshop]

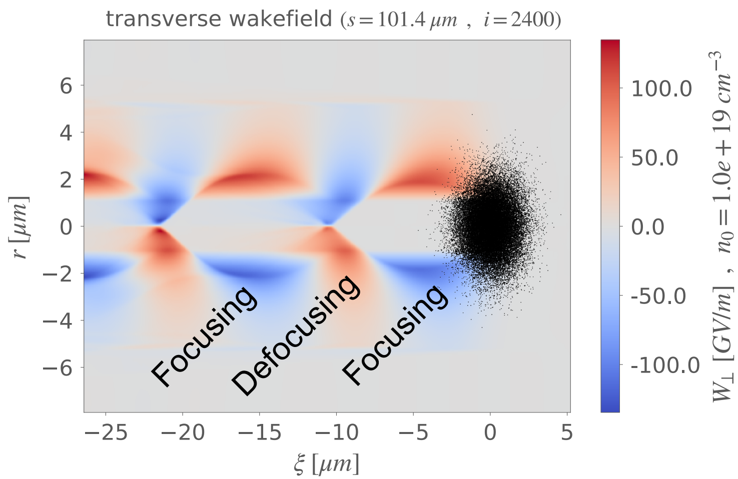
2D hollow plasma PIC simulations

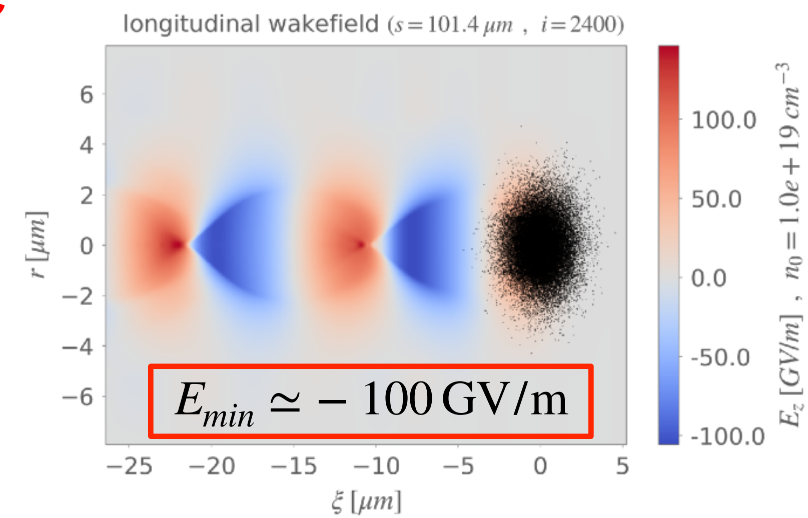
- Single channel model. Beam-driven





FBPIC

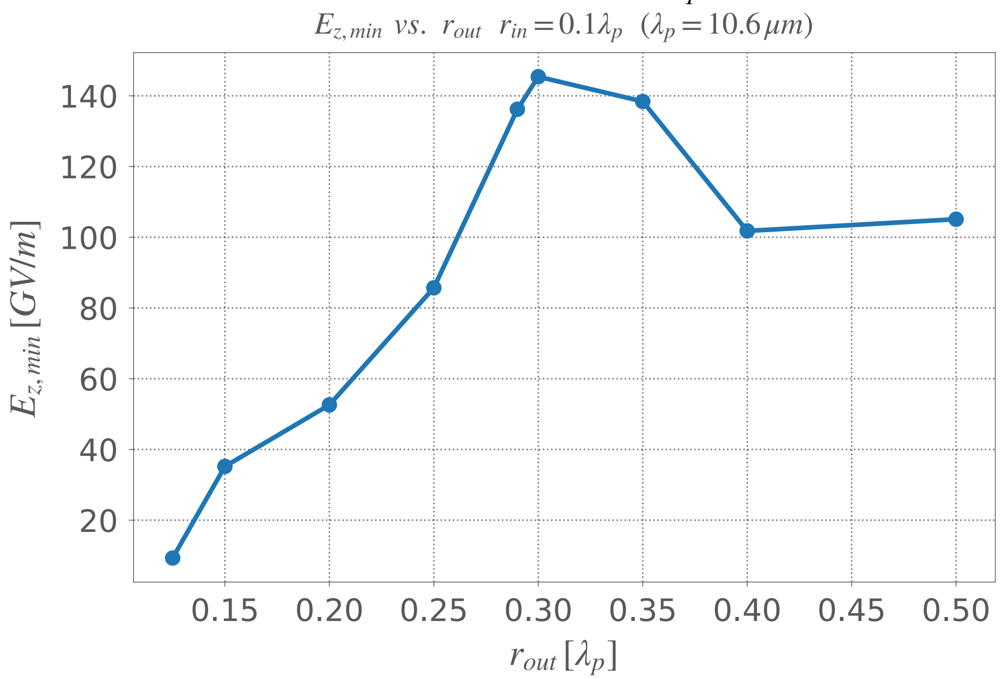




2D hollow plasma PIC simulations

- Single channel model. Beam-driven. Wall thickness scan

Acc. gradient as a functions of the outer radius, keeping an inner radius $r_{in} = 0.1\lambda_p$



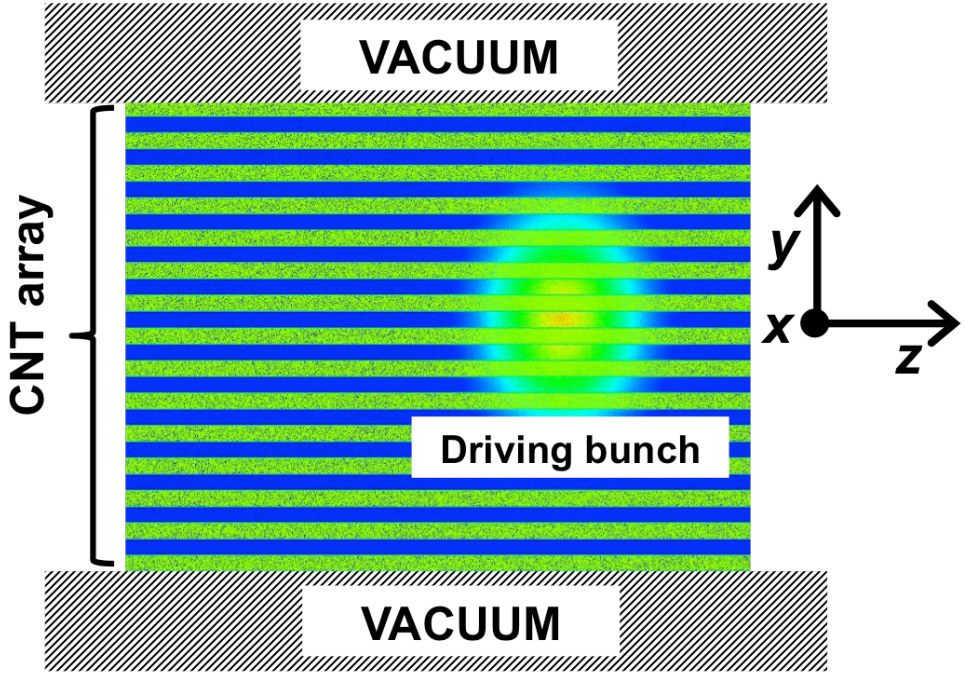
CNT external radius in units λ_p

It seems that there is an optimal value for the thickness to excite the strongest E_z

Multi-hollow plasma simulations

- CNT array model, alternating hollow channels and plasma walls inside a vacuum chamber. 2D PIC simulations with **EPOCH**

Cartesian coordinates



[J. Resta-Lopez et al., IPAC2018]

Driving e⁻ beam parameters:

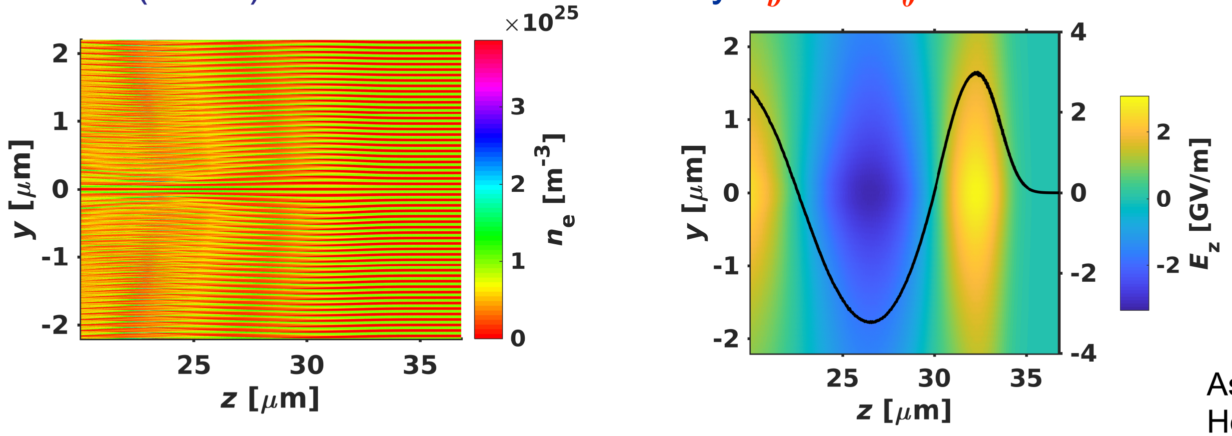
Energy	200 MeV
Energy spread	1%
Bunch population	5×10^6
rms radius	$168(0.1c/\omega_p)$ nm
rms length	$840(0.5c/\omega_p)$ nm
peak density	10^{25} m^{-3}

Assuming:
Hollow radius: 20 nm
Wall thickness: 40 nm
Wall plasma density: $n_0=10^{25}$ m^{-3}

Multi-hollow plasma simulations

- 2D PIC simulations with **EPOCH**

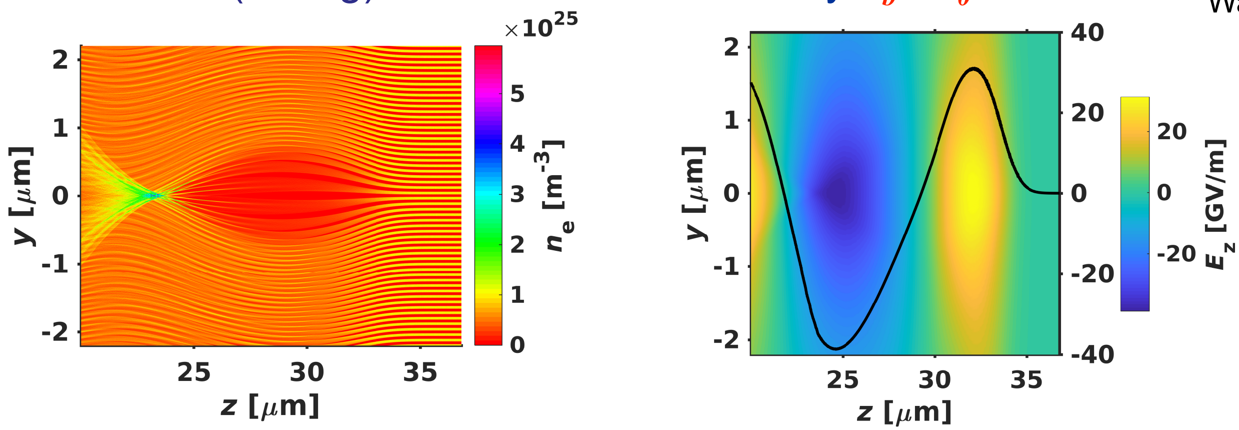
Linear (weak) driver. For beam density $n_b = 0.1 n_0$



$E_z \approx 3\ \mathrm{GV/m}$

Assuming:
Hollow radius: 20 nm
Wall thickness: 40 nm
Wall plasma density: $n_0 = 10^{25}\ \mathrm{m^{-3}}$

Non-linear (strong) driver. For beam density $n_b = n_0$



$E_z \approx 40\ \mathrm{GV/m}$

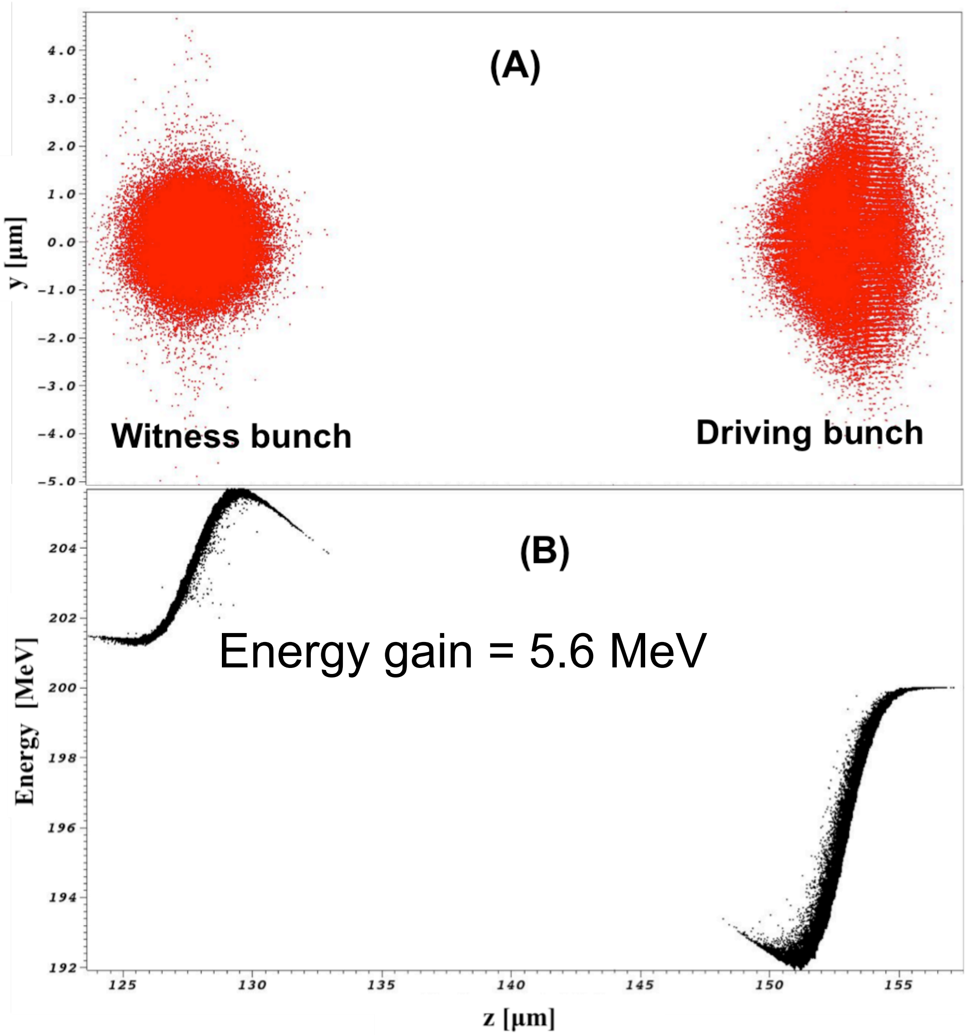
Multi-hollow plasma simulations

- For beam density $n_b = n_0$

Benchmarking:
2D PIC simulations with **VSim**

$$E_z \approx 40 \text{ GV/m}$$

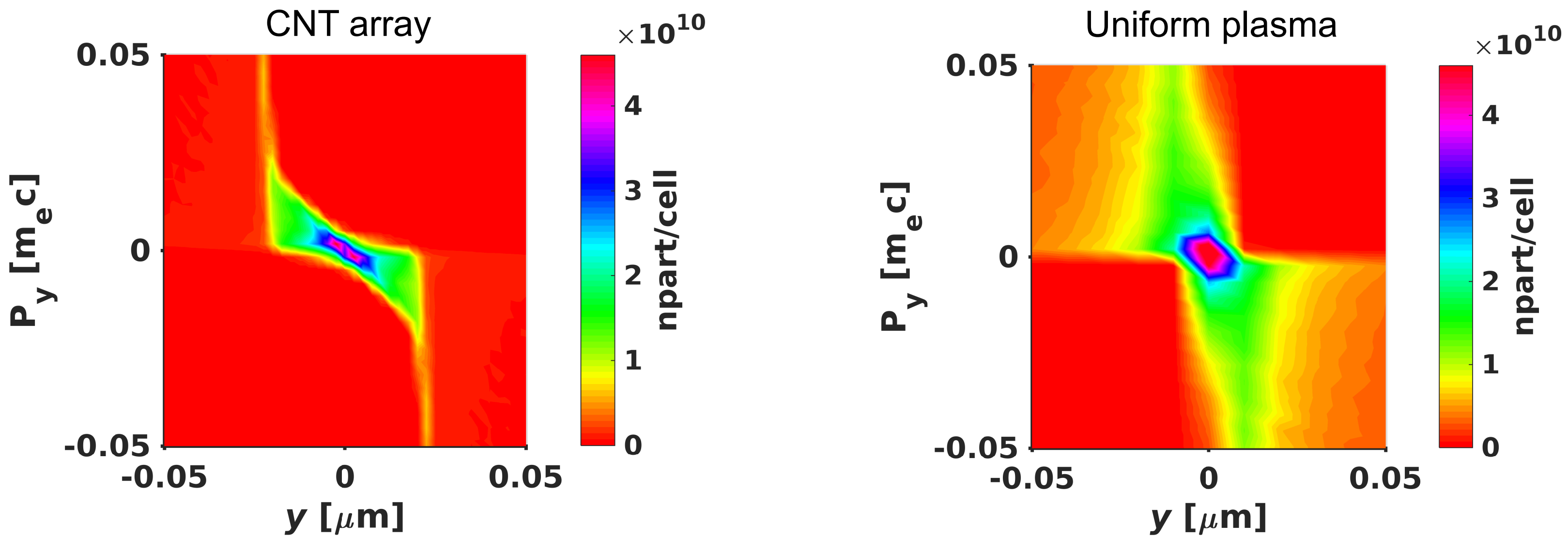
Assuming:
Hollow radius: 20 nm
Wall thickness: 40 nm
Wall plasma density: $n_0 = 10^{25}$ m^{-3}



Multi-hollow plasma simulations

- For beam density $n_b = n_0$. 2D PIC simulations with **EPOCH**

Transverse phase space. CNT array vs. uniform plasma



- CNTs can efficiently cool the transverse phase space of channelled beam particles in a similar way to natural crystals

- Focusing and collimation by transverse fields generated from the oscillating surface plasmon

Multi-hollow plasma simulations

- More recent simulations.

[See A. Bonatto presentation.This workshop]

e-beam:

$k_p\sigma_z = 0.5$

$k_p\sigma_r = 0.1$

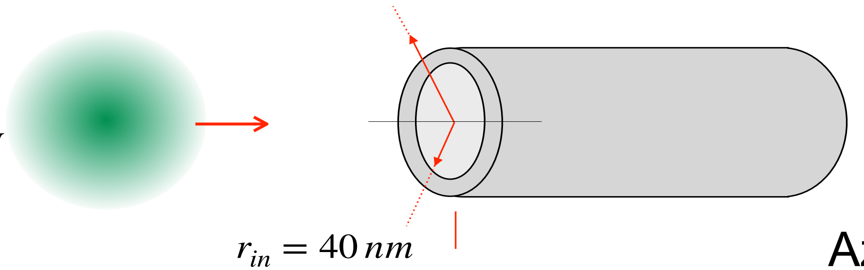
$E_{k0} = 0.2\,\mathrm{GeV}$

$Q_b = 0.6\,\mathrm{pC}$

$n_b/n_0 = 1$

$r_{out} = 80\,nm$

CNT:



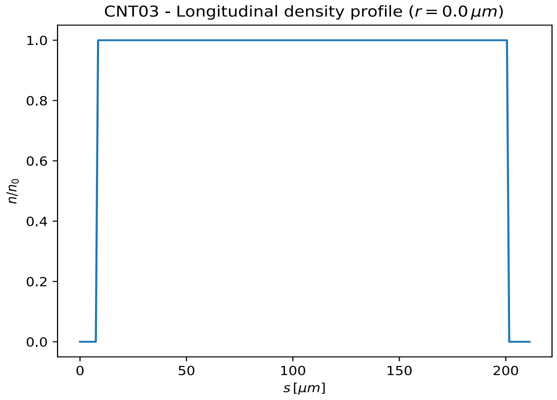
$r_{in} = 40\,nm$

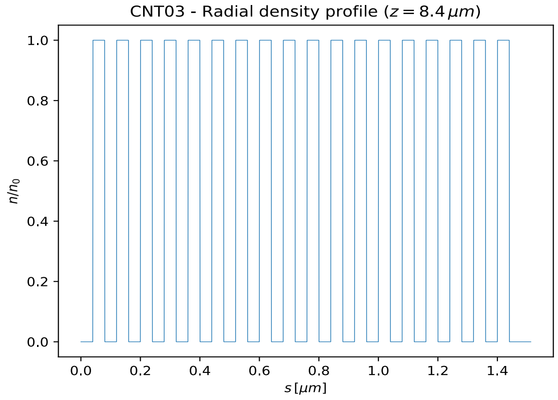
plasma:

$n_0 = 1 \times 10^{25}\,\mathrm{m}^{-3}$

Azimuthal symmetry
Concentric 40 nm CNTs

- Multiple CNTs evenly spaced (wall thickness = gap = $40\,nm$):

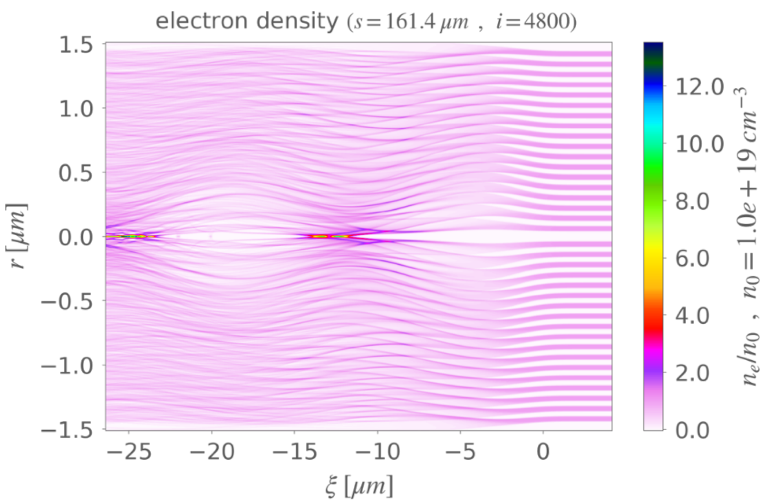


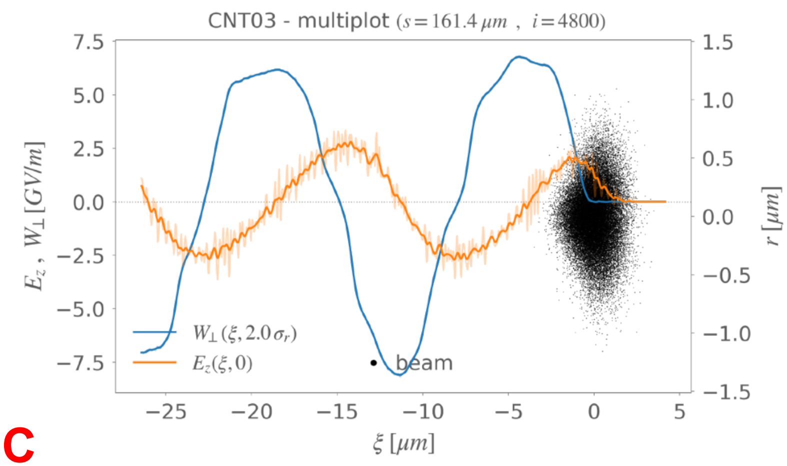


Multi-hollow plasma simulations

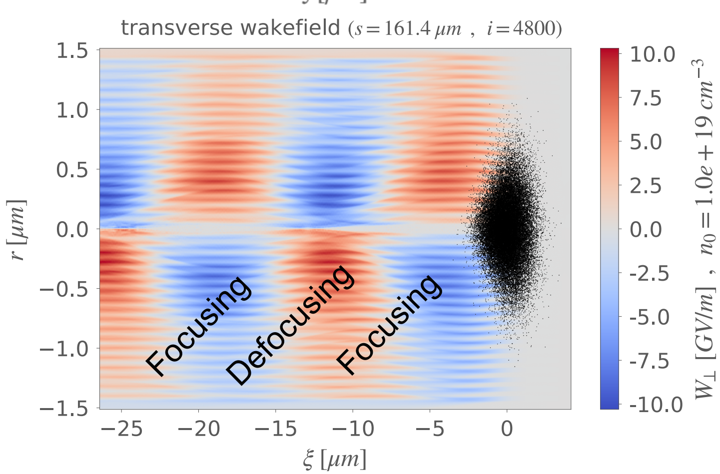
- More recent simulations.

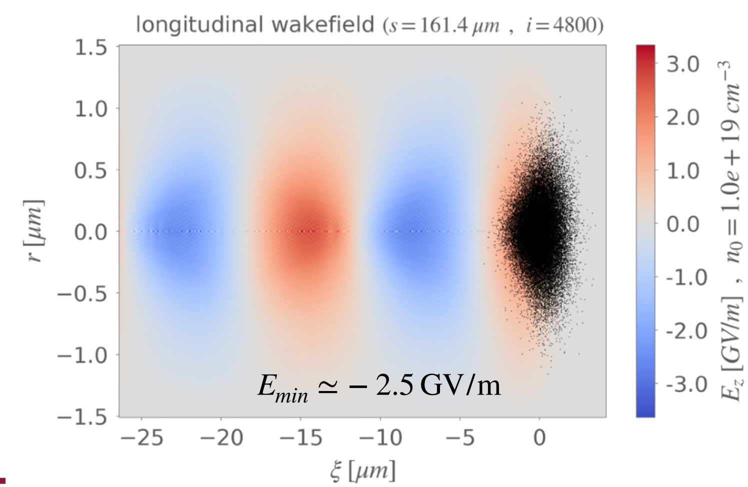
[See A. Bonatto presentation.This workshop]



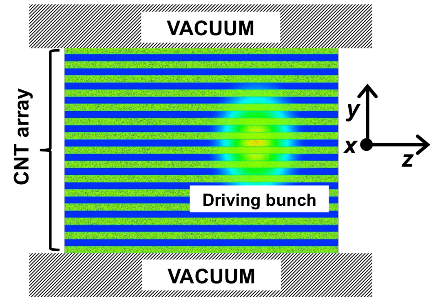


FBPIC





Towards CNT arrays



- Existing 2D and 3D PIC codes are either
  - Cartesian
  - Cylindrically symmetric (no good for azimuthal modes)
  - 3D Fourier-Bessel cylindrical grids about single axis (no good for arrays)

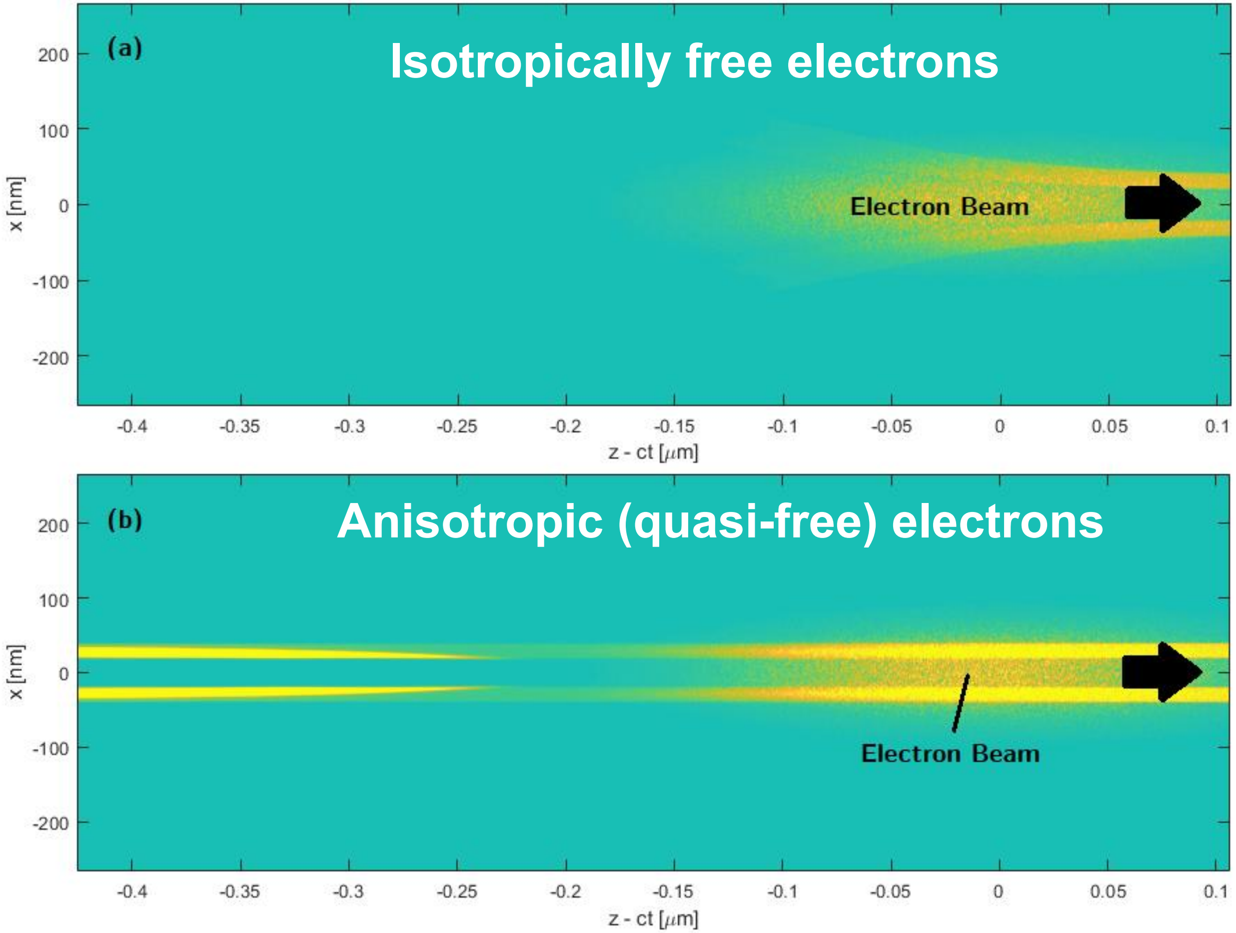
- If CNT walls are **ionised**:
  - **Best choice:** Cartesian 3D codes (quasi-static may be good enough for co-propagating electrostatic modes)

- If CNT walls are **unionised**:
  - existing 3D PIC codes must be adapted to simulate bound electrons on multiple embedded 2D cylinders
  - **Best choice:** Cartesian 3D codes (probably)
  - we have modified the 3D EPOCH code to model nanotube wall electrons as plasma in a static positive "jellium" background

3D semi-rigid wall CNT model

- Preliminary simulation results. **EPOCH**

[See A. Perera's poster for details. This workshop]

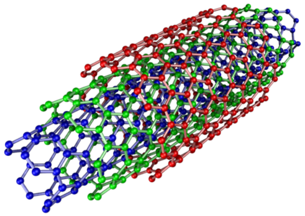


Electron currents in walls restricted to longitudinal and azimuthal directions (unless fully ionized)

3D CNT array model

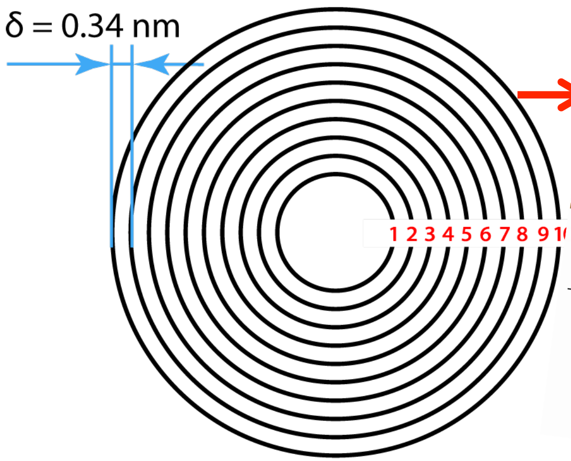
- Based on multi-walled CNTs

PIConGPU code

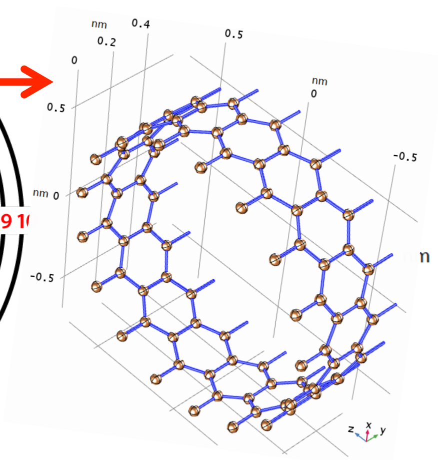


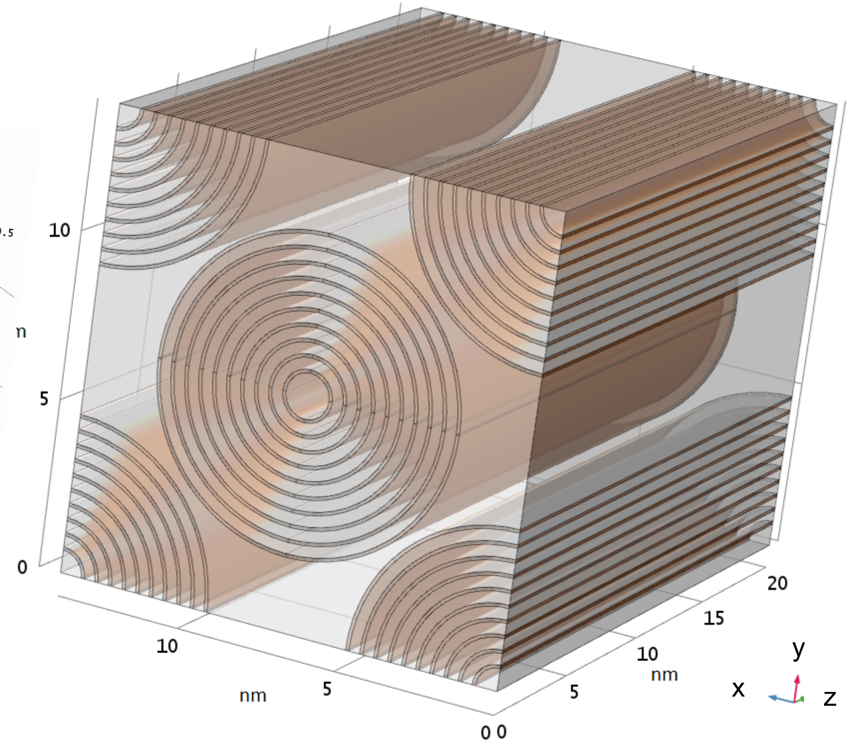
CNT array unit (square packing)

Discrete cell unit



0.1 nm thick layers





Calculated density ~ 10^{28} atoms/m^3

Test beam facilities

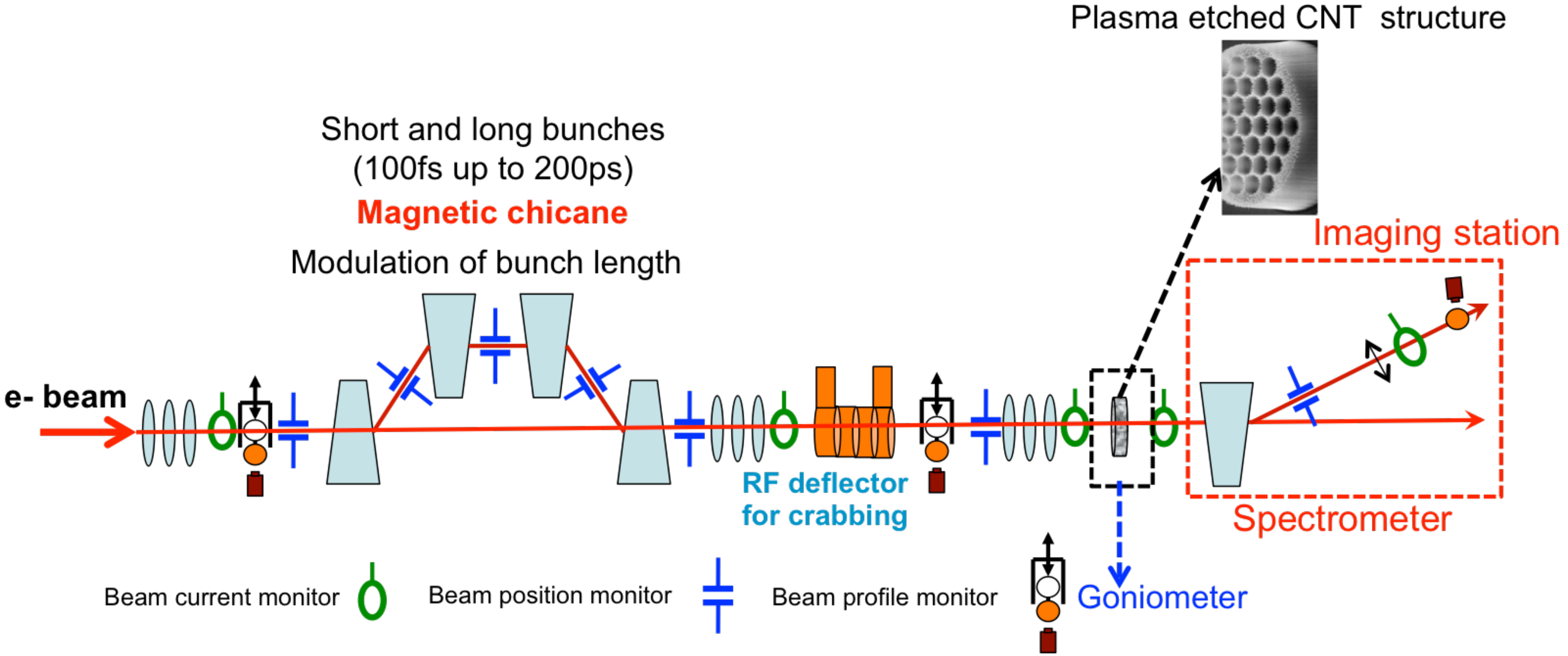
- Where a proof-of-concept might be performed (tbd). For example

Parameter	CLEAR (CERN)	CLARA (DL)	FLASHForward (DESY)*	PITZ (DESY)
Energy	200 MeV	250 MeV	400-600 MeV	21.5 MeV
Energy spread	< ±2%	±1%	0.2%	-
Trans. norm. emittance (rms)	< 20 mm-mrad	≤ 1 mm-mrad	x/y ~2.5/5 mm mrad	0.37 mm mrad
Bunch length (rms)	< 0.75 ps	0.1-0.25 ps (short pulse)	4 μm (12 fs)	14.5 ps
Bunch charge	0.6 nC	0.1-0.25 nC	0.2-0.3 nC	0.1 nC
Peak bunch density	$\sim 10^{21}$ m^{-3}	<~ 10^{22} m^{-3}	$\sim 10^{24}$ m^{-3}	$\sim 10^{18}$ m^{-3}
Bunch spacing	0.667 ns	--	< 1 μs	-
Nb. of bunches	1-32-226	1	-	-
Repetition rate	[0.8, 5] Hz	10 Hz	1-10 Hz (macro) 0.04-3 MHz (micro)	10 Hz

* EuPRAXIA, LWFA type beam parameters: 1 GeV case

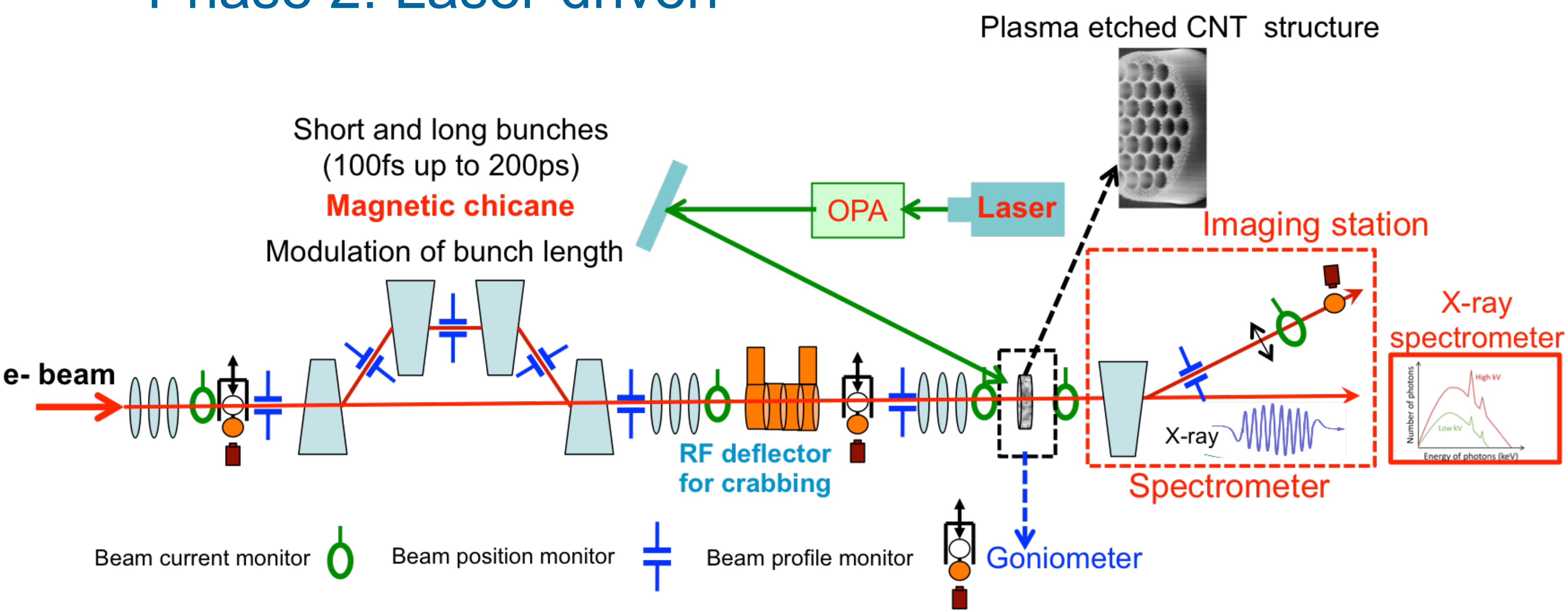
Experimental layout

- Phase 1: Beam-driven



Experimental layout

- Phase 2: Laser-driven



Investigate the tunability of a photo-excited CNT array to be used as compact X-ray source

Summary and perspective

- The use of solid nano-structures may open new possibilities to obtain high particle acceleration gradients beyond those provided by standard RF
- Assuming plasma wakefield excited by a driving bunch, preliminary simulation results show the possibility of obtaining longitudinal electric accelerating gradients > 10 GV/m
- Channelling and efficient cooling of transverse phase space
- New test beam facilities, such as CLEAR, CLARA, FLASHForward, etc. might offer the opportunity to carry out proof-of-concept tests of CNT based wakefield acceleration
- CNT structures open up exciting new avenues for compact particle acceleration and radiation sources

Future plan

- Simulation of multiple CNTs to investigate fields in CNT arrays
- Study of coupled-CNT operation
- Optimization studies of wall-thickness, nanotube radius crystalline geometry and array properties
- Establish a detailed experimental plan, considering available test beam facilities
- Collaborations

Special thanks to

Cristian Bontoiu, Volodymyr Rodin, Carsten P. Welsch,
University of Liverpool

Alex Bonatto, Guoxing Xia,
University of Manchester

Thank you

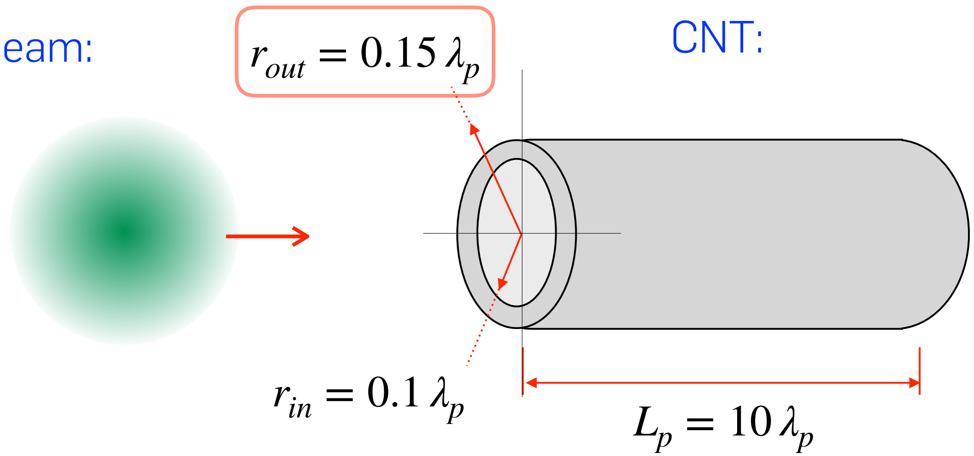
Backup slides

2D hollow plasma PIC simulations

- Single channel model. Beam-driven. Reduced thickness

e-beam:

$$\sigma_z = 0.1\,\lambda_p$$
$$\sigma_r = 0.1\,\lambda_p$$
$$E_{k0} = 1\,\mathrm{GeV}$$
$$Q_b = 33\,\mathrm{pC}$$
$$n_b/n_0 = 1.1$$

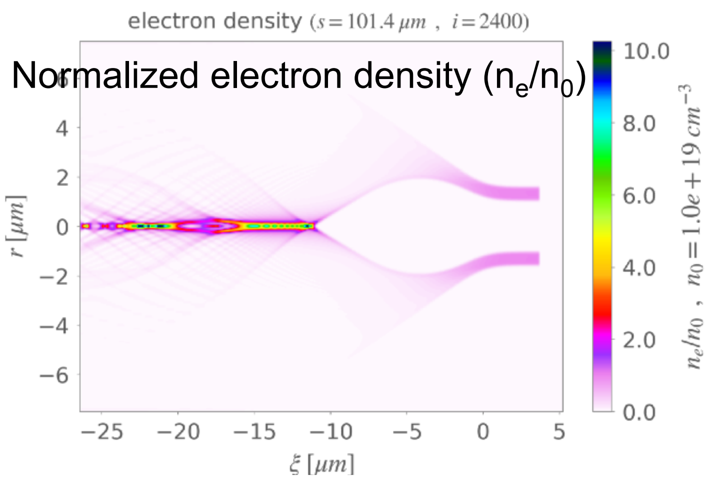


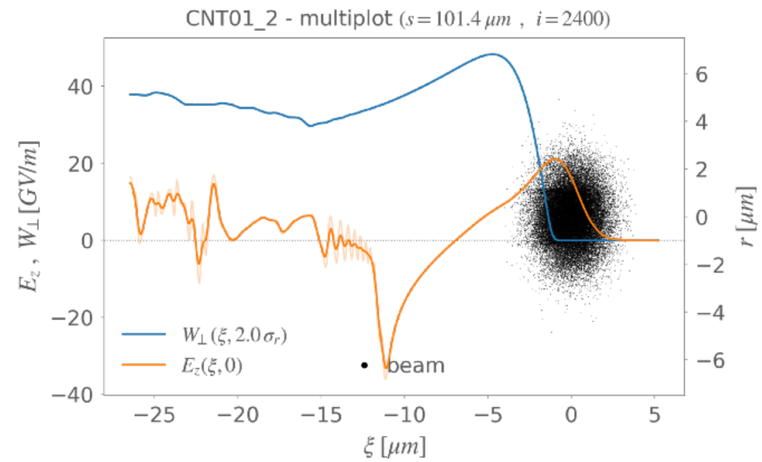
plasma:

$$n_0 = 1 \times 10^{25}\,\mathrm{m}^{-3}$$
$$\lambda_p \simeq 10.6\,\mu\mathrm{m}$$
$$E_0 \simeq 0.3\,\mathrm{TV/m}$$

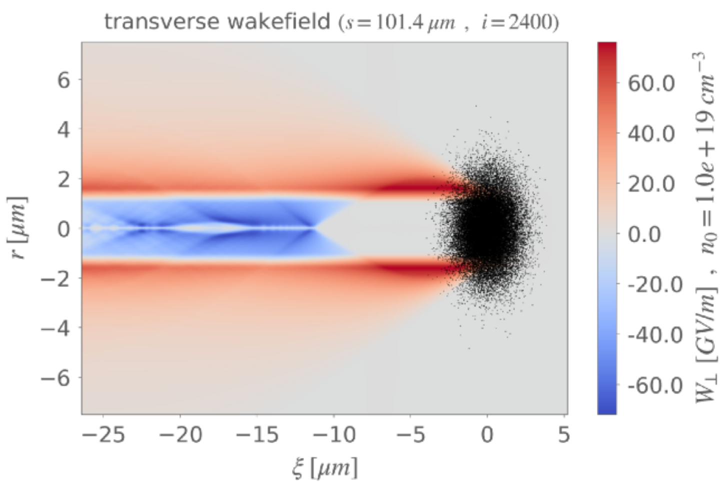
2D hollow plasma PIC simulations

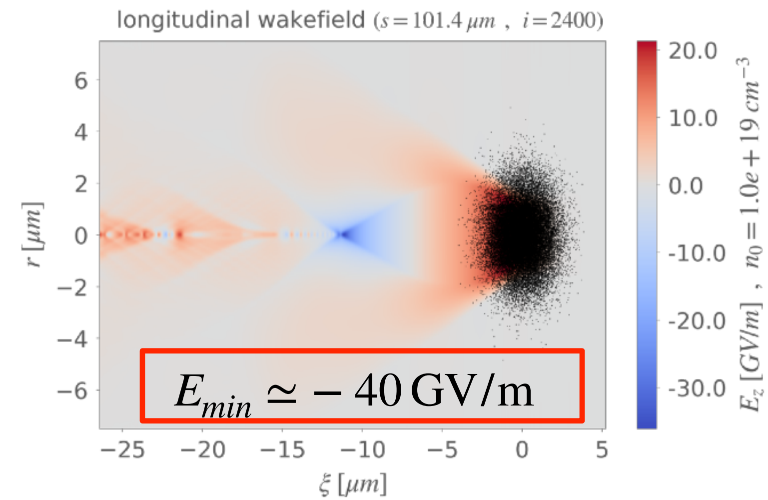
- Single channel model. Beam-driven. Reduced thickness





FBPIC





3D CNT array model

- Dimensions and density

- with the C=C bond length taken as a = 0.1425 nm the atoms density can be calculated if one chooses an axial unit 3a long;

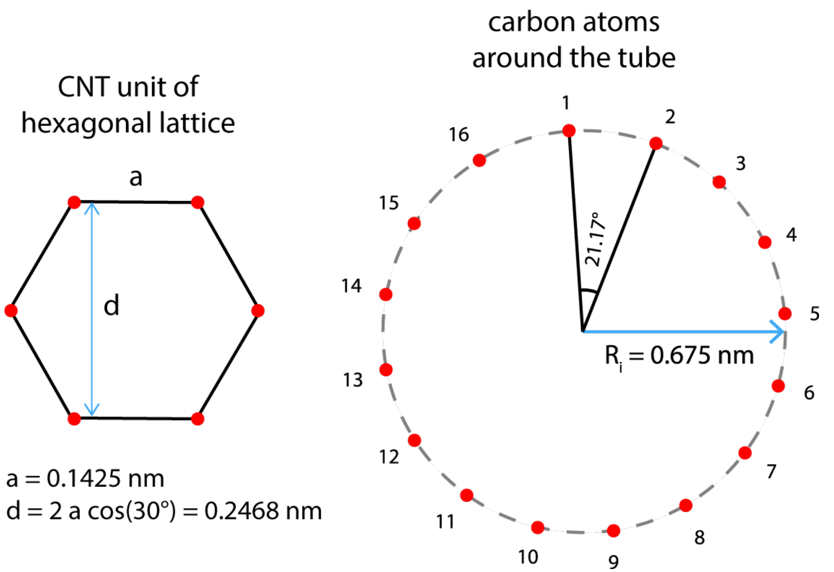


Figure 1.4 *Distribution of Carbon atoms around the tube.*

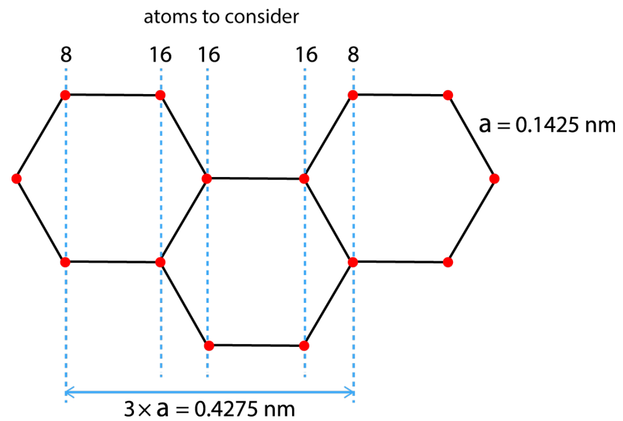


Figure 1.5 *View of the Carbon atoms distributed in hexagons.*

3D CNT array model

- Dimensions and density

- volume of the inner tube is:

$$V = 2\pi \frac{D_i}{2} t \times 3a = 0.181\, nm^3 \tag{1.1}$$

- density of atoms:

$$\rho = \frac{64\, atoms}{0.181\, nm^3} = 352.988 \times 10^{27} \frac{atoms}{m^3} \tag{1.2}$$

- all 10 layers have a volume of v = 1.135 nm^3 and they contain

$$v \times \rho = 400.646\, atoms \tag{1.3}$$

which yields a scaled down density of:

$$\frac{400.646\, atoms}{v} = 13.559 \times 10^{27} \frac{atoms}{m^3} \tag{1.4}$$

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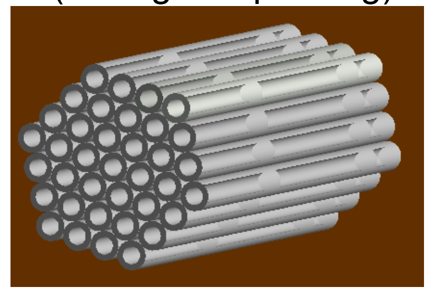
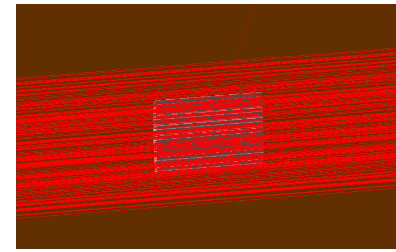
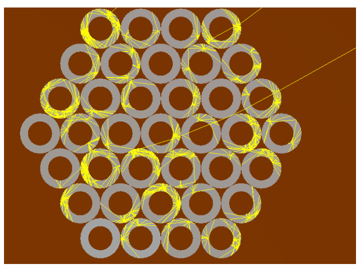
Scattering studies

- 3D array of CNT made of usual Carbon
- Tube radius – 50 nm
- Wall thickness – 20 nm
- Length – 2 μm
- Steps inside volume < 2 nm
- **Geant4 QGSP BIC + EmDNA model**

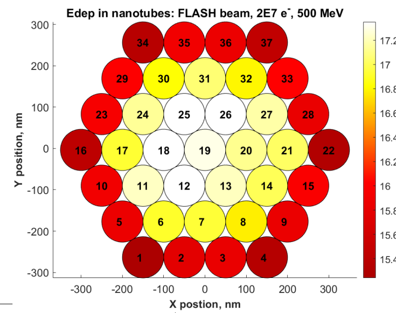
(Hexagonal packing)



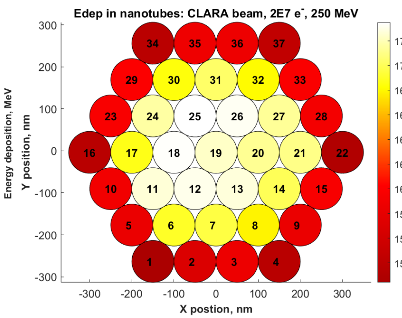




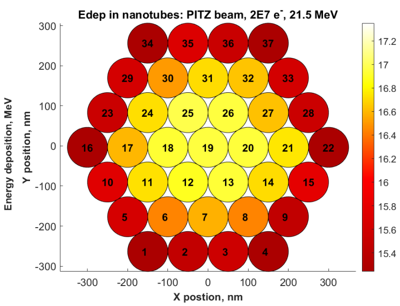
FLASHForward

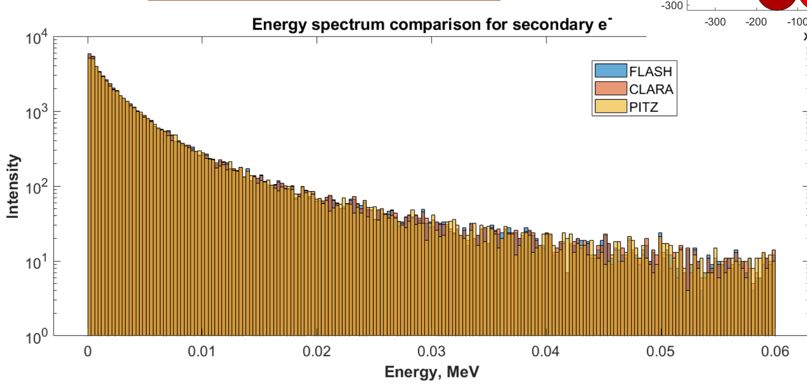


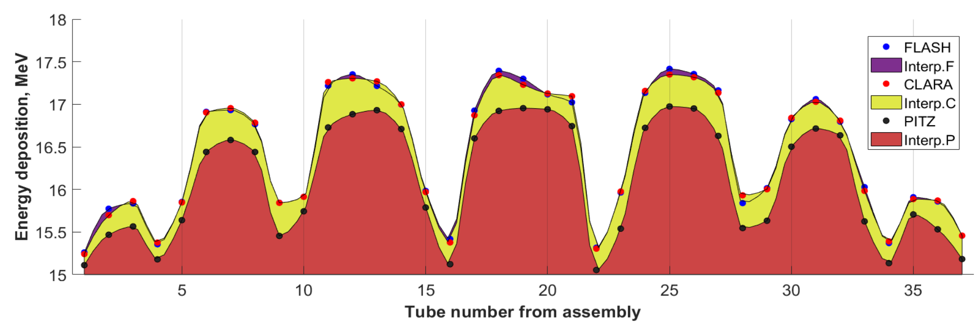
CLARA



PITZ







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