

Study of Ultra-High Gradient Acceleration in CNT arrays

Javier Resta López

The University of Liverpool and Cockcroft Institute



TRAINING THE
NEXT GENERATION
OF **PARTICLE**
ACCELERATOR
EXPERTS

Outline

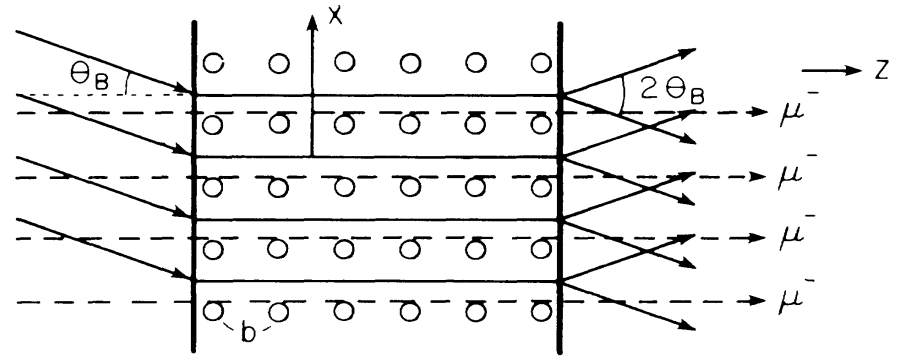
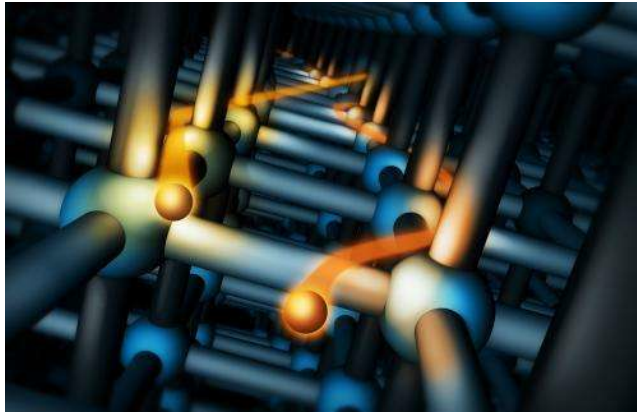
- Motivation
- Context
- State-of-the-art
- Simulations
- Experimental layout
- Summary

Motivation

- Conventional RF accelerator technology limited to ~ 100 MV/m
- In principle, density of gaseous plasma is limited to below $\sim 10^{24}$ m⁻³, which corresponds to wakefields up to ~ 100 GV/m
- An alternative to pursue larger plasma density is to use solid state based plasma, such as metallic crystals or CNT
- Density of conduction electrons in solids: 10^{24} m⁻³ $< n_e < 10^{30}$ m⁻³
- In recent years, CNT structures have attracted new attention as an alternative way to generate ultra-high acceleration gradients > 100 GV/m

Context

- Earlier work
 - X-ray LWFA in crystals

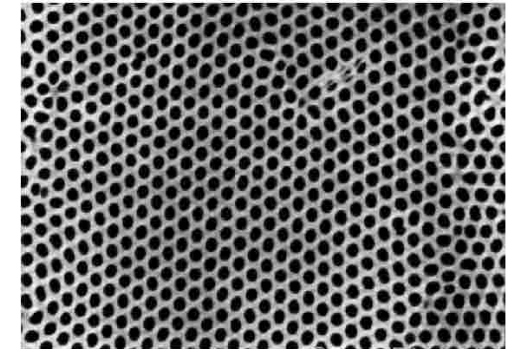
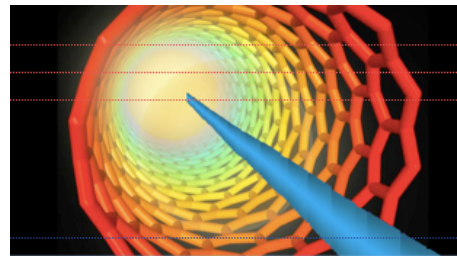


T. Tajima and M. Cavenago, PRL 59 (1987) 1440
 P. Chen and R. J. Noble, AIP Conf. Proc. **156** (1987) 222
 T. Tajima et al., Particle Accelerators 32 (1989) 235

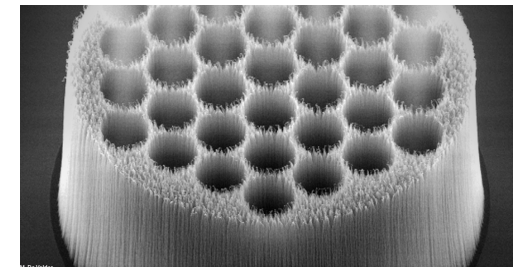
- Accelerating fields $\sim 1-100$ TV/m
- Channelled particles confined to the rows of atoms by electric fields of the order of $10-100$ GV/m
- Crystals excited by TW or PW fs lasers
- Crystal have been used in accelerators as collimators and bending elements

Context

- Earlier work
 - Wakefield acceleration in porous nanomaterials
 - Advantages of CNT w.r.t. natural crystals:
 - Higher acceptance: CNT channel size $\sim(1-100)$ nm; channel size for Si crystal $\sim \text{\AA}$
 - Lower dechanneling rate
 - Lower stopping power
 - Significantly higher thermal and mechanical robustness: suitable for channeling acceleration of MW beams
 - Great degree of dimensional flexibility
 - Wakefield drivers:
 - Beam
 - High power laser



Porous alumina – 100 nm



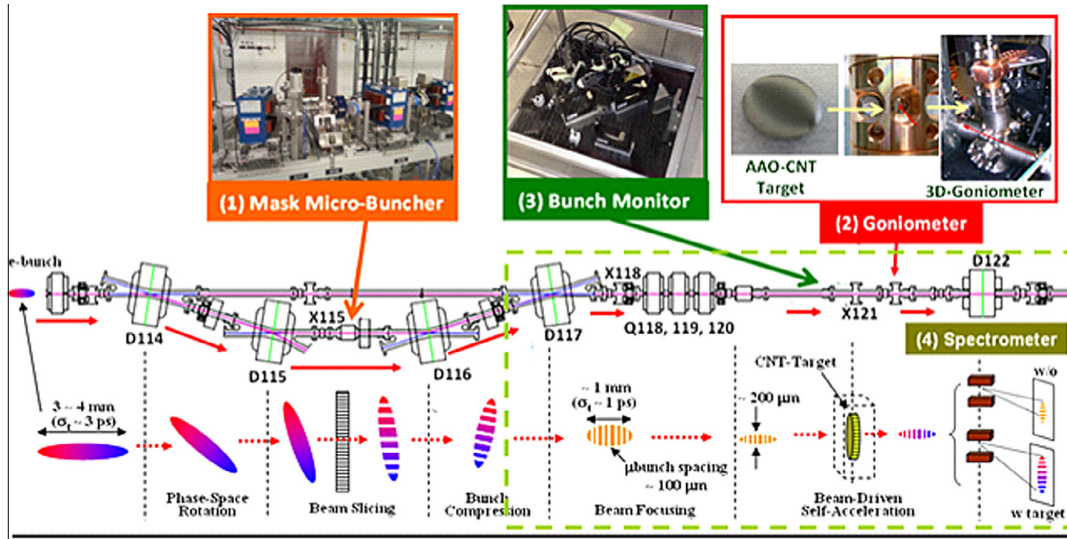
CNT array
Michael De Volder et al.,
Uni. of Cambridge

State-of-the-art

- Earlier experimental proposals

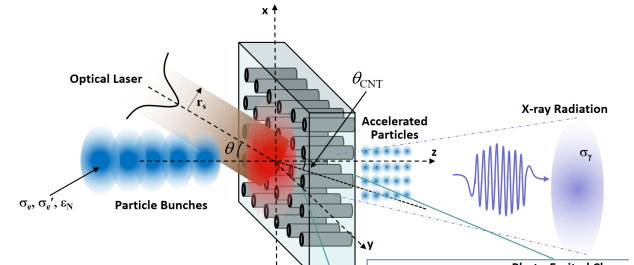
Y. M. Shin et al.

ASTA 50 MeV beamline @ Fermilab

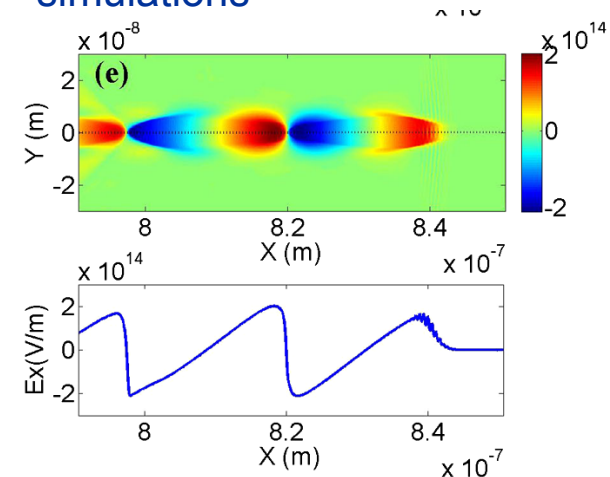


Y. M. Shin, NIM B 335 (2015) 94
 Y. M. Shin, NIM B 407 (2017) 276
 Y. M. Shin, Phys. of Plasmas 24 (2017) 023115
 X. Zhang et al., PRST-AB 19 (2016) 101004

- Coherent X-ray radiation from photo-excited CNT

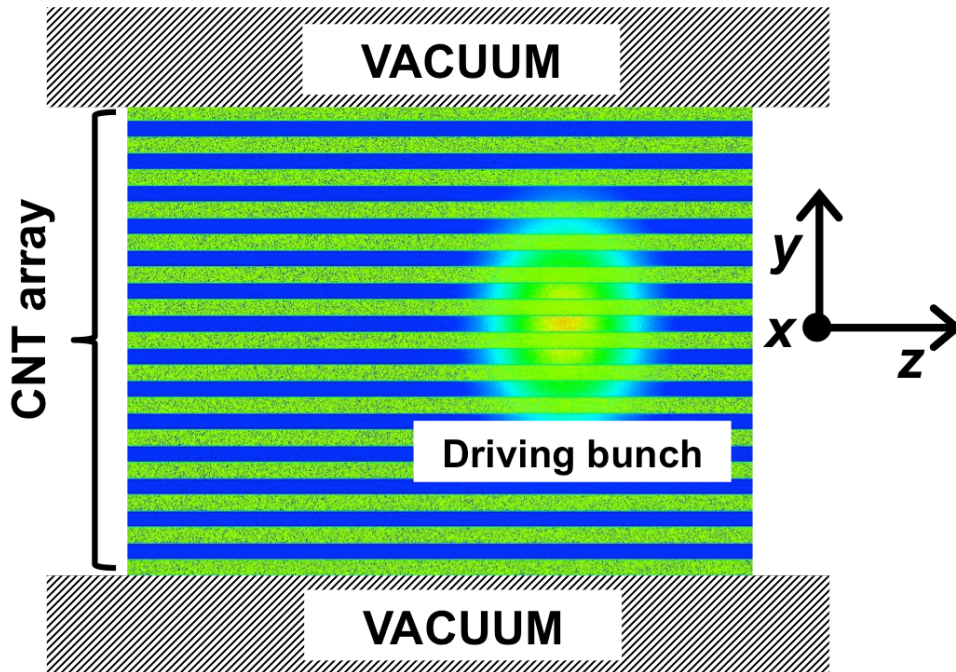


- LWA in a single CNT channel simulations



CNT array simulations

- Multi-hollow plasma model of a CNT array using the PIC code EPOCH, alternating hollow channels and plasma walls inside a vacuum chamber



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

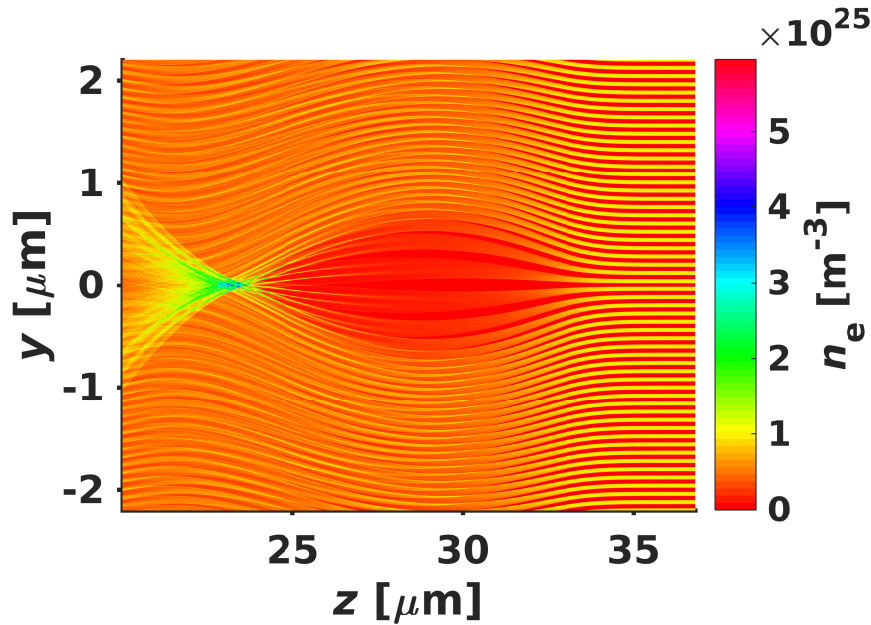
Wall thickness: 40 nm

Wall plasma density: $n_e = 10^{25} \text{ m}^{-3}$

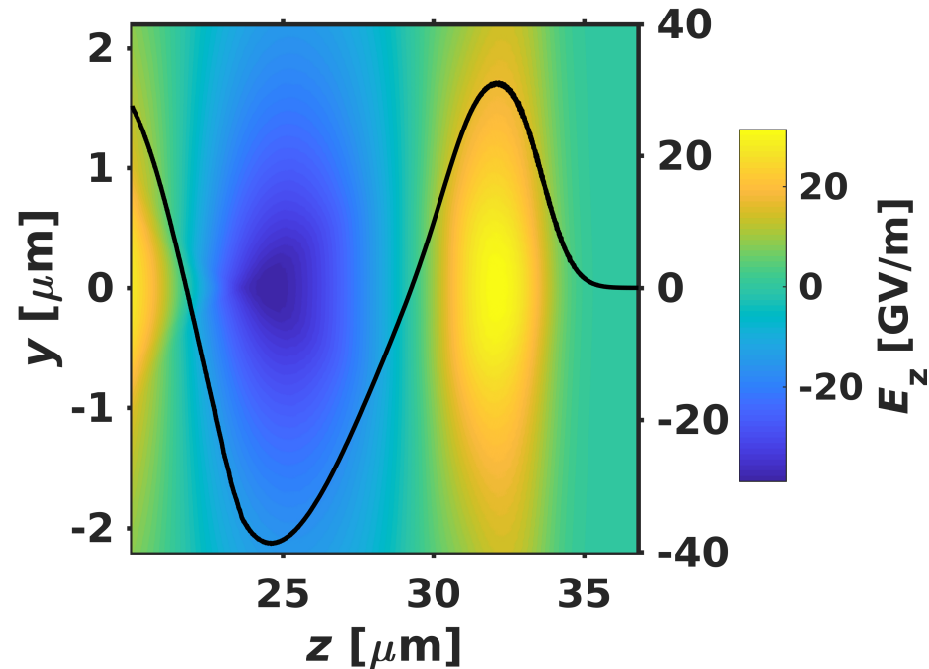
Longitudinal wakefield

- For beam density $n_b = n_e$

Plasma electron density perturbation



Longitudinal electric field

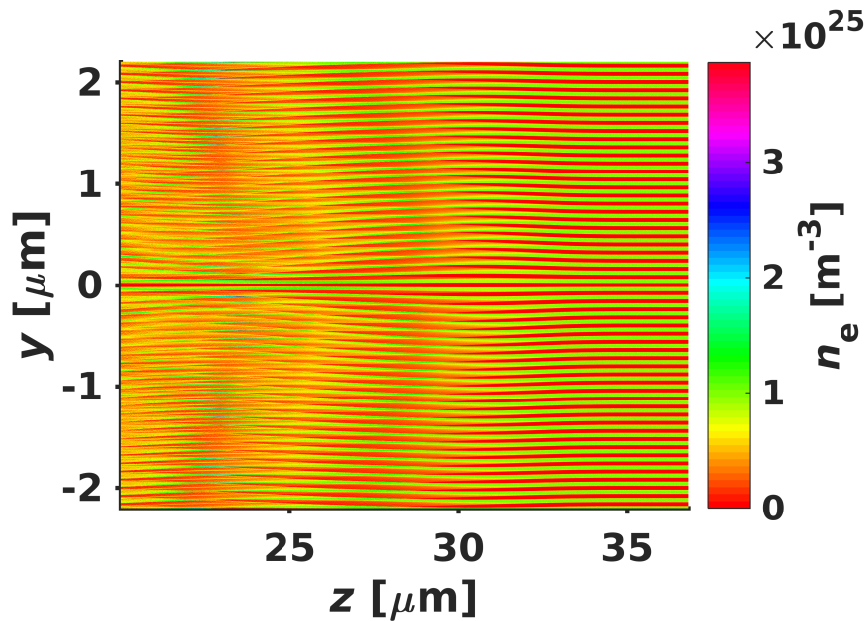


$$E_z \approx 40 \text{ GV/m}$$

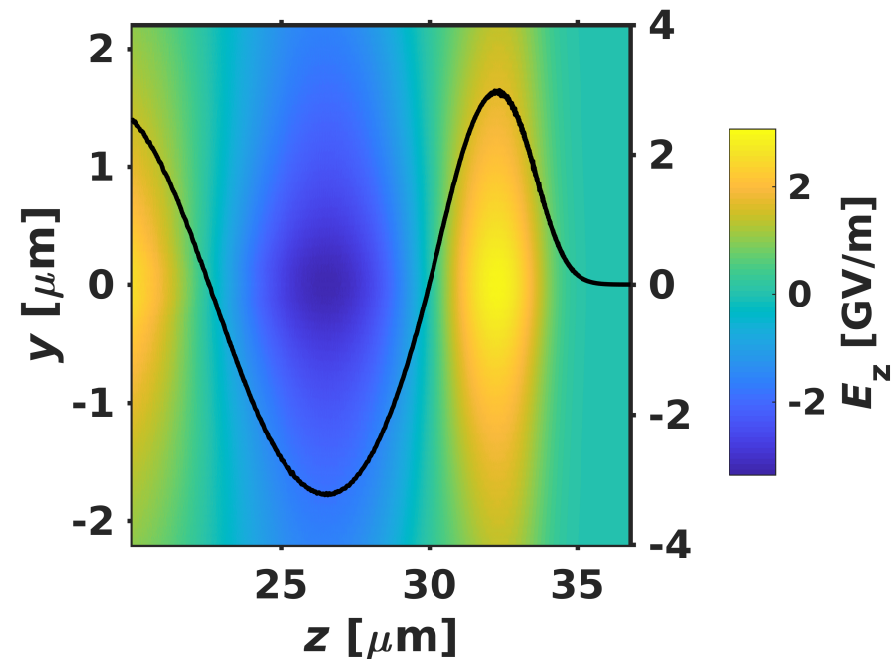
Longitudinal wakefield

- For beam density $n_b = 0.1 n_e$

Plasma electron density perturbation



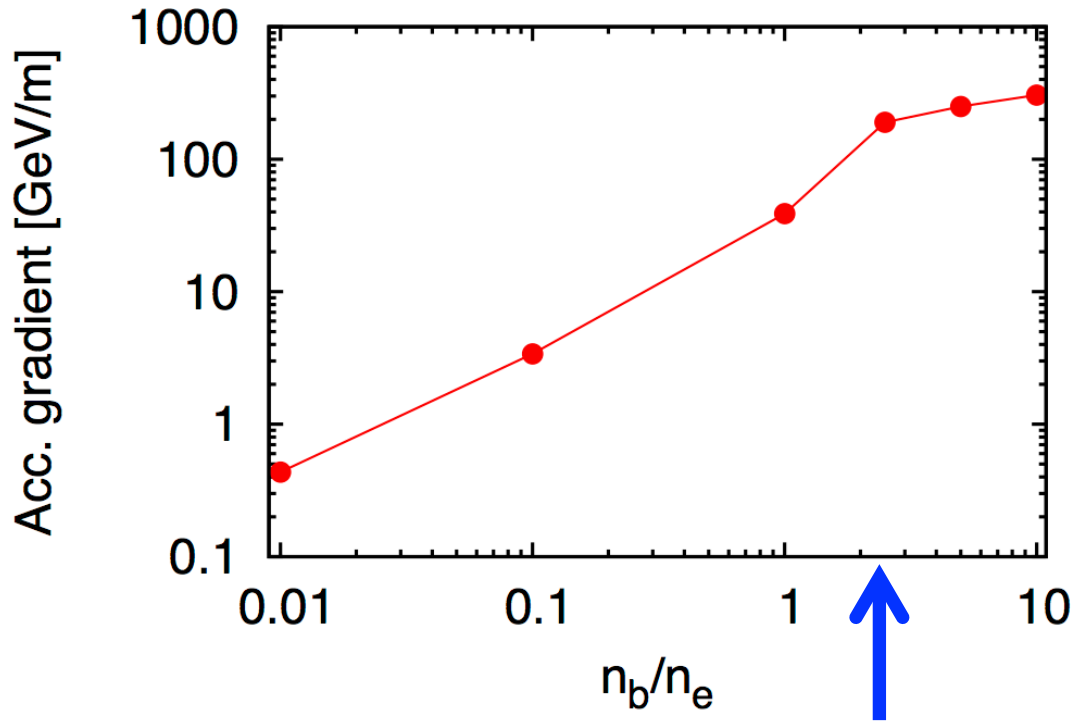
Longitudinal electric field



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

Acc. gradient scaling

- Accelerating gradient vs driving bunch density



Wave-breaking limit:

For $n_e = 10^{25} \text{ m}^{-3}$

$$\omega_p = \sqrt{e^2 n_e / (m_e \epsilon_0)}$$

$$\simeq 1.8 \times 10^{14} \text{ s}^{-1}$$

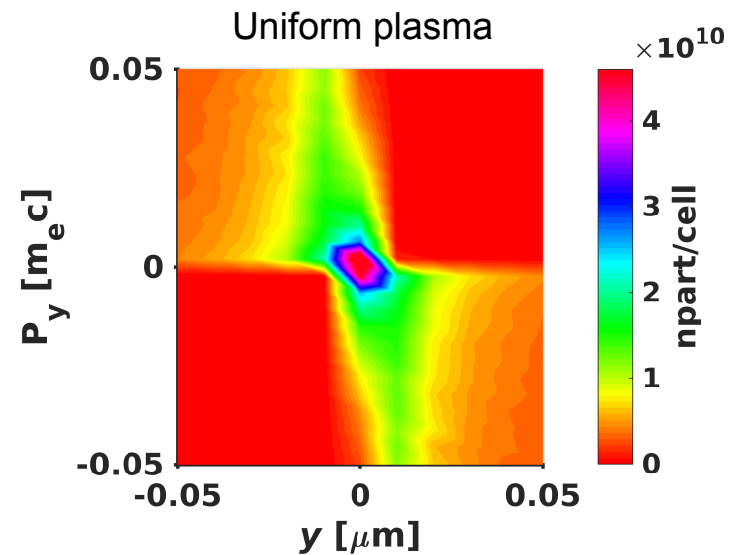
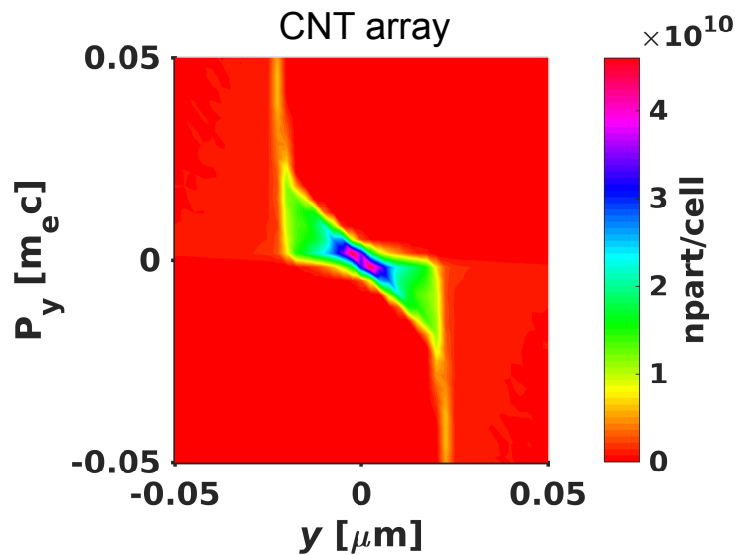
$$E_z = m_e c \omega_p \simeq 305 \text{ GV/m}$$

reached when $n_b \approx 10 n_e$

When $n_b \approx 2.5 n_e$ the beam plasma interaction transfers from the linear to the nonlinear regime

CNT array vs uniform plasma

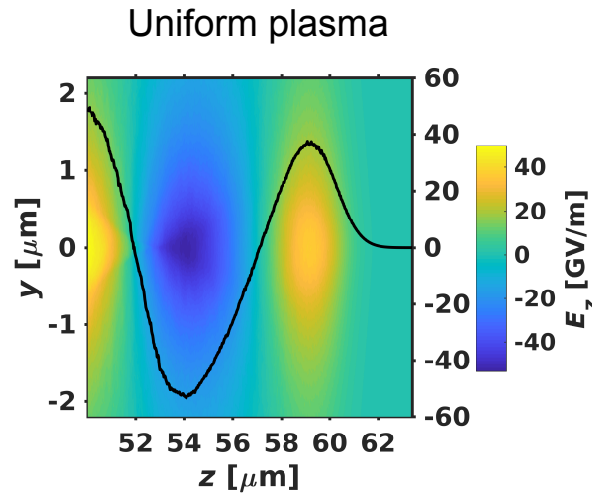
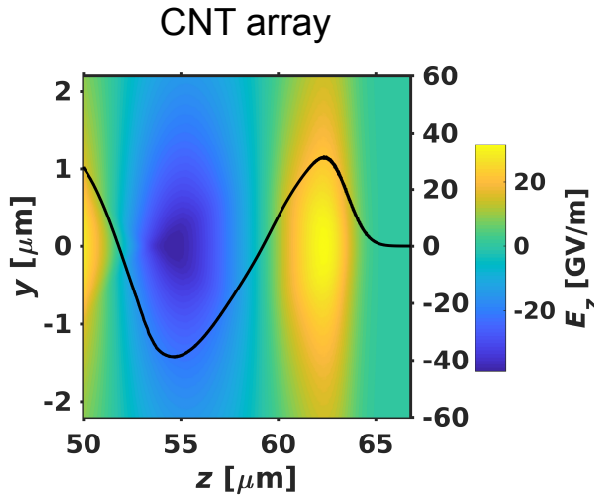
- Transverse phase space
 - For $n_b = n_e$:



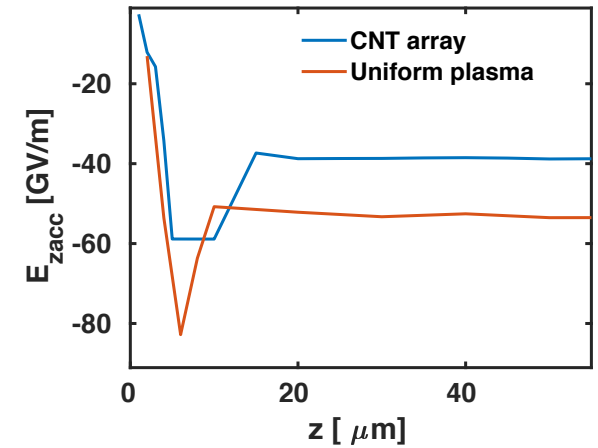
- CNTs can efficiently cool the transverse phase space of channelled beam particles in a similar way to natural crystals
- Focusing and collimation by transverse fields generated from the oscillating surface plasmon

CNT array vs uniform plasma

- Longitudinal wakefield
 - For $n_b = n_e$:



Maximum acceleration gradient vs propagation distance



- We pursue larger plasma density (e.g. solid state plasma) to get larger acc. gradient. However the driving particles will get detrimental scattering in a solid uniform plasma
- CNT array can also provide a large acc. field meanwhile reducing the transverse momenta of the channelled beams

Experimental facilities

- Where a proof-of-concept might be performed

Parameter	CLEAR (CERN)	CLARA (DL)	ASTA (FNAL)
Energy	200 MeV	250 MeV	[5, 50] MeV
Energy spread	< $\pm 2\%$	$\pm 1\%$	$\sim \pm 0.01\%$
Trans. norm. emittance (rms)	< 20 mm-mrad	≤ 1 mm-mrad	[0.1, 100) mm-mrad
Bunch length (rms)	< 0.75 ps	0.1-0.25 ps (short pulse)	$\sim [0.0001, 0.1]$ ps
Bunch charge	0.6 nC	0.1-0.25 nC	$\sim [0.02, 20]$ nC
Bunch spacing	0.667 ns	--	< 10 ns to 10 s
Nb. of bunches	1-32-226	1	3000
Repetition rate	[0.8, 5] Hz	10 Hz	[0.1, 5] Hz

Experimental layout

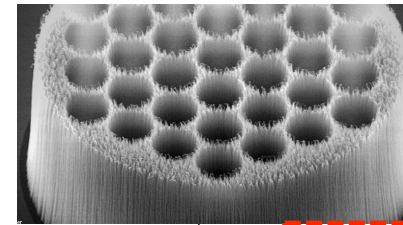
- Design based on CLEAR beamline:

Short and long bunches
(100fs up to 200ps)

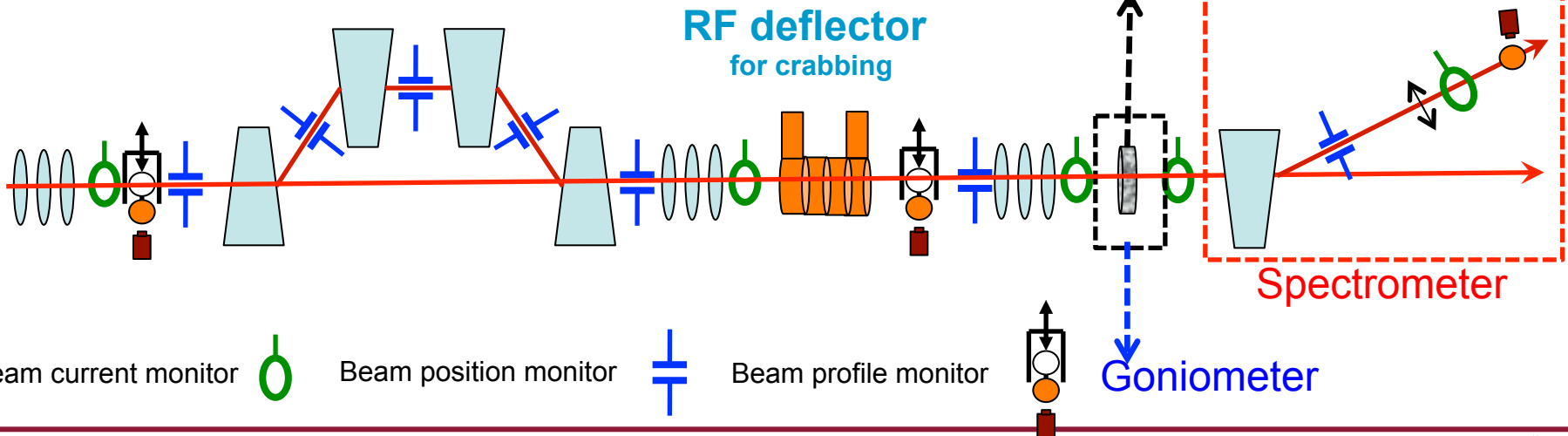
Magnetic chicane

Modulation of bunch length

Plasma etched CNT structure



Imaging station



Energy gain

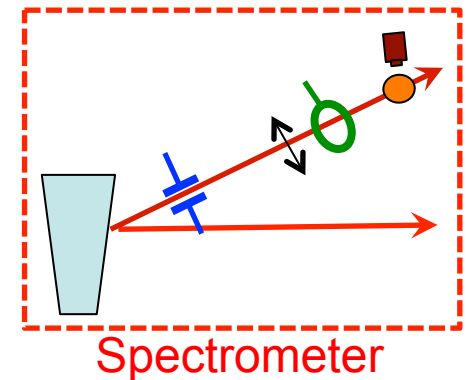
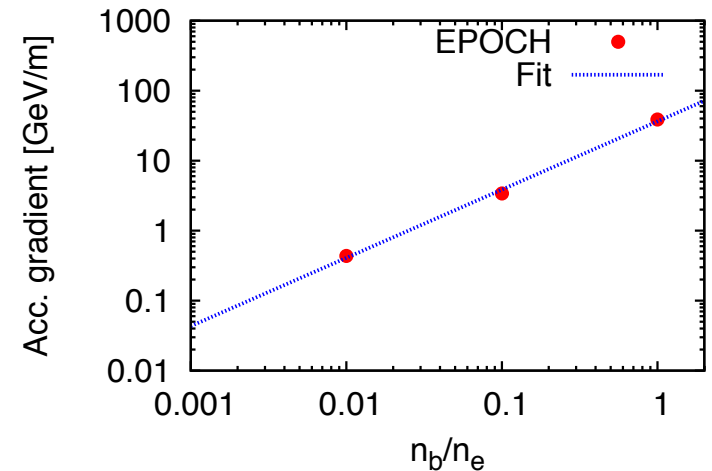
- For example, if CLEAR or CLARA beam parameters pushed to match a beam density $n_b \sim 0.001 n_e$:

- Accelerating field: $E_z \approx 40 \text{ MV/m}$
- Assuming 1 mm length CNT array:
- Energy gain:

$$\Delta W \approx 40 \text{ keV}$$

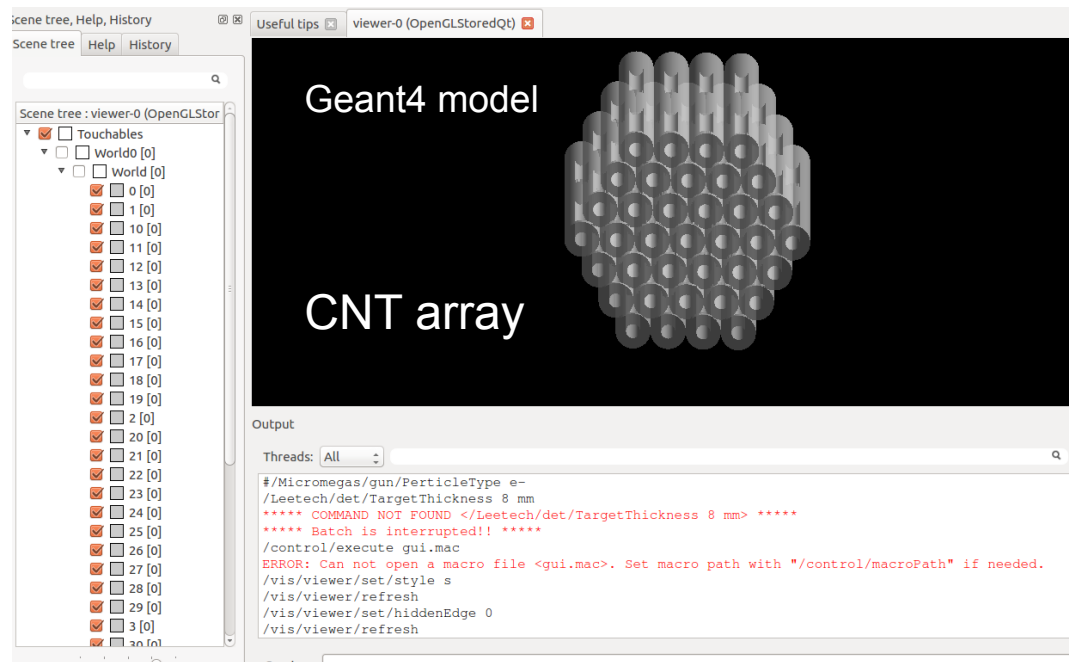
- Spectrometer resolution of $\lesssim 10 \text{ keV}$ will be required
- For example, a magnetic spectrometer with energy resolution $\Delta W/W = 5 \times 10^{-5}$, such as the ILC-type spectrometer for beam energy calibration

V. Duginov et al., DESY Report, LC-DET-2004-031



Thermo-mechanical robustness

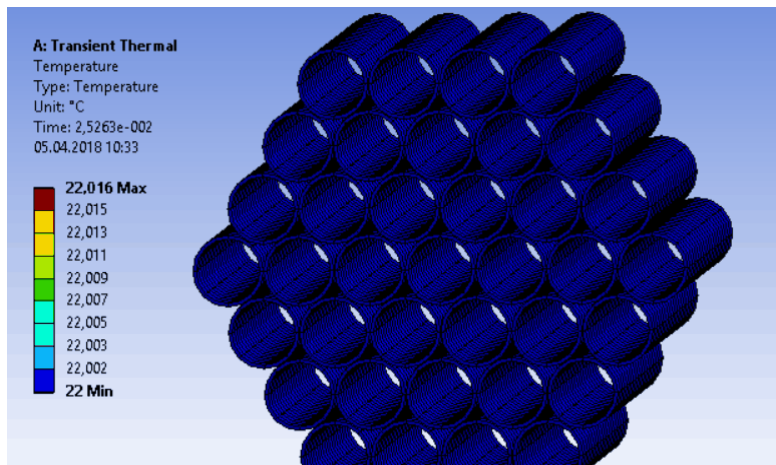
- Thermal conductivity of CNTs is about 20 times higher than that of natural crystals (e.g. silicon) and the melting point of a freestanding single-tip CNT is $\sim 3000\text{-}4000\text{ K}$
- High mechanical strength, tensile strength $>100\text{ GPa}$ (100 x Stainless-steel)



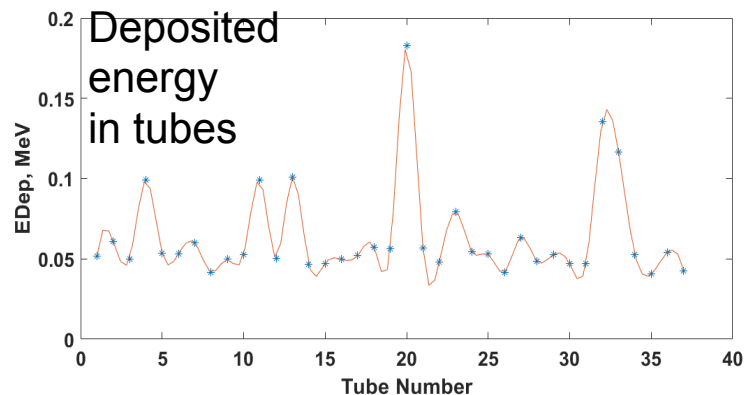
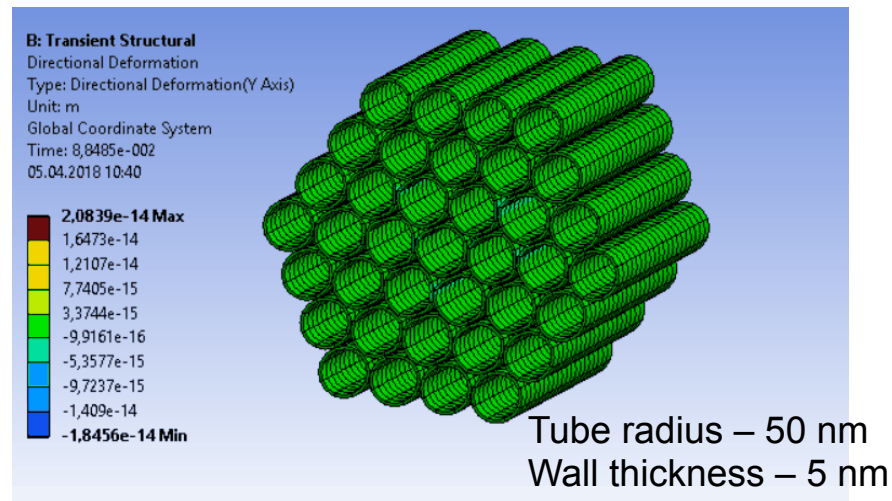
Thermo-mechanical robustness

- Model in **GEANT4** and **ANSYS**: assuming a CLARA-type driving beam

Heating



Mechanical stress



$$\Delta T_{max} \approx 273.17 \text{ K}$$

Maximum structural deformation $\sim 10 \text{ fm}$

Structure resilience:

Restoring force acts faster than repetition rate

Summary

- The use of **solid nano-structures** may open new possibilities to obtain high particle acceleration gradients beyond those provided by standard RF
- Simulations based on a **2D multi-hollow plasma**
- Assuming plasma wakefield excited by a driving bunch, preliminary 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** and **CLARA** 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**

Special thanks to

Alexandra Alexandrova, Yangmei Li, Volodymyr Rodin,
Yelong Wei, Carsten P. Welsch, Guoxing Xia and
Yuan Zhao

Thank you