Solid Plasma-based Wakefield Accelerators

EuPRAXIA Camp I: Technologies

Dr. Bifeng Lei, QUASAR group

bifeng.lei@liverpool.ac.uk

University of Liverpool, The Cockcroft Institute

8st Apirl.2025, PISA, Italy

The Cockcroft Institute of Accelerator Science and Technology

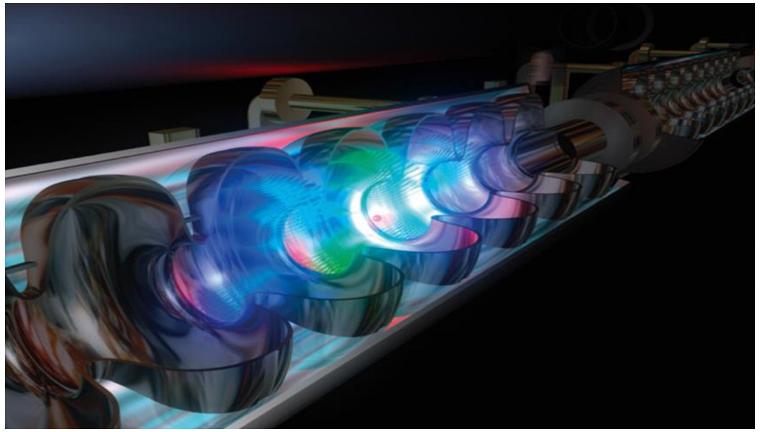
UNIVERSITY OF LIVERPOOL

QUASAR GROUP

Introductions & Motivation

Conventional accelerator

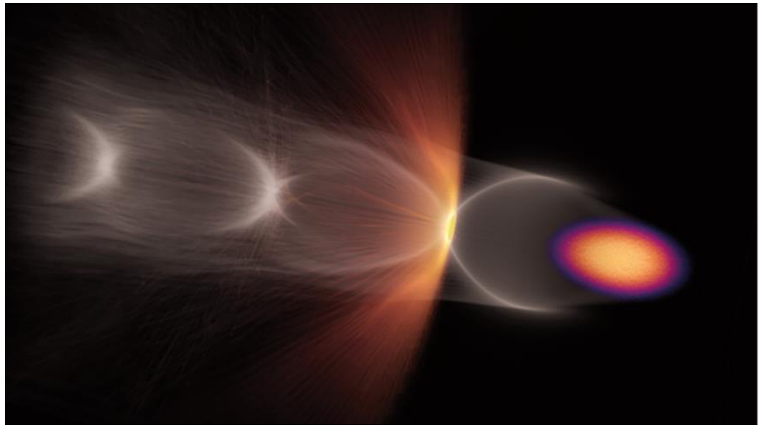
100 MV/ m



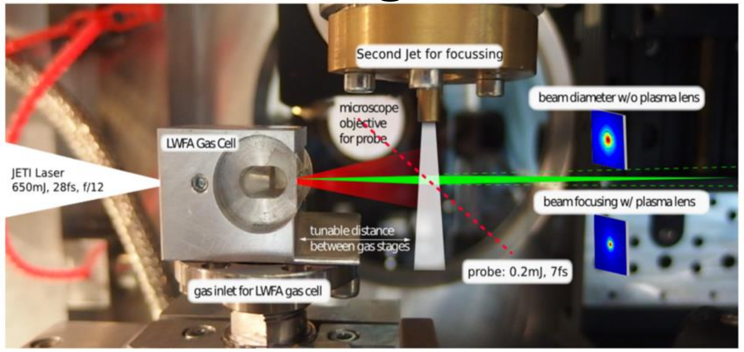
LHC@CERN

Gaseous plasma accelerator

100 GV/m

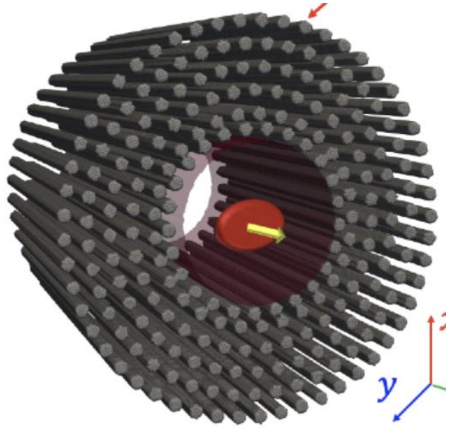


LWFA@HIJ



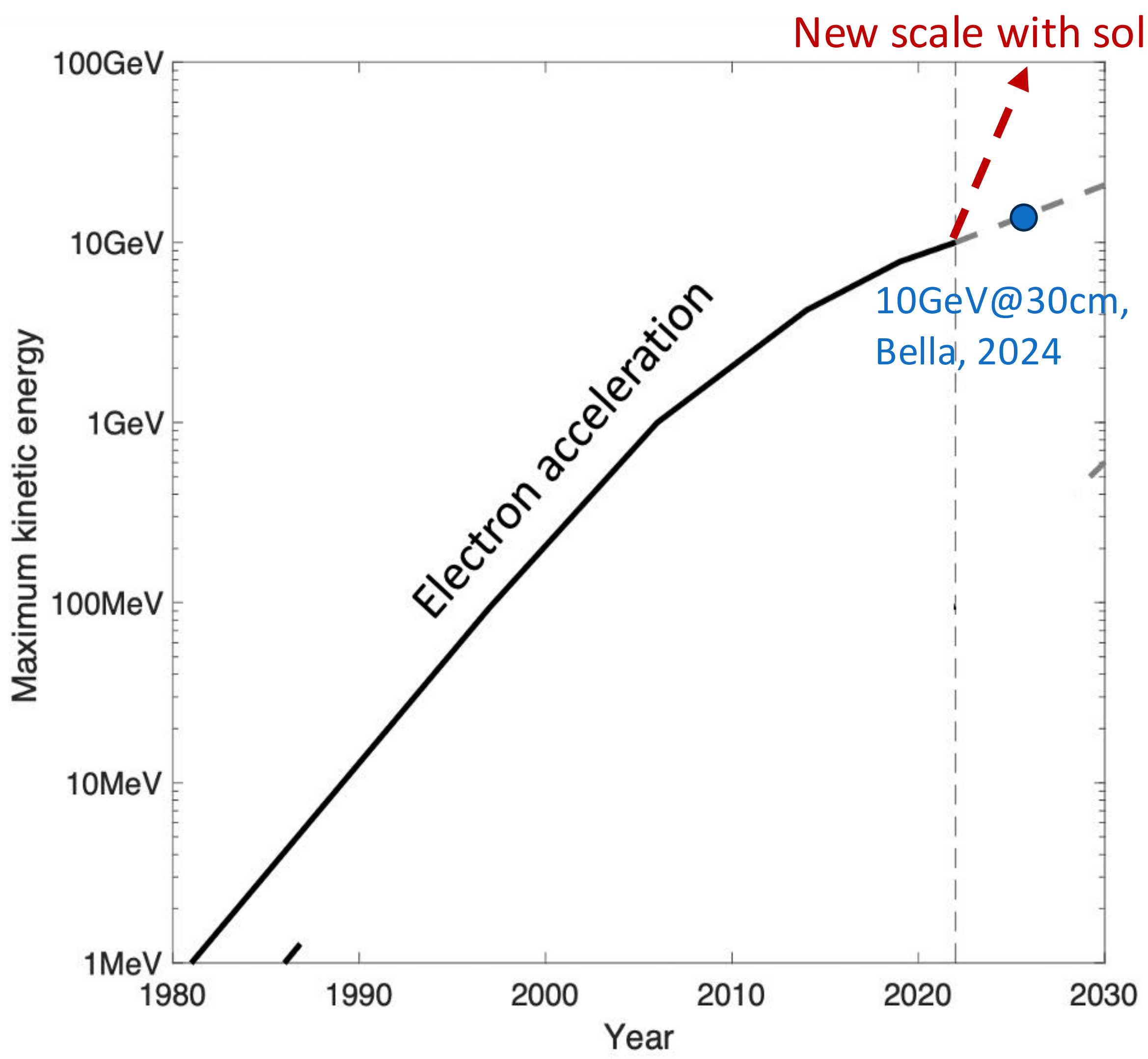
Solid-density plasma accelerator

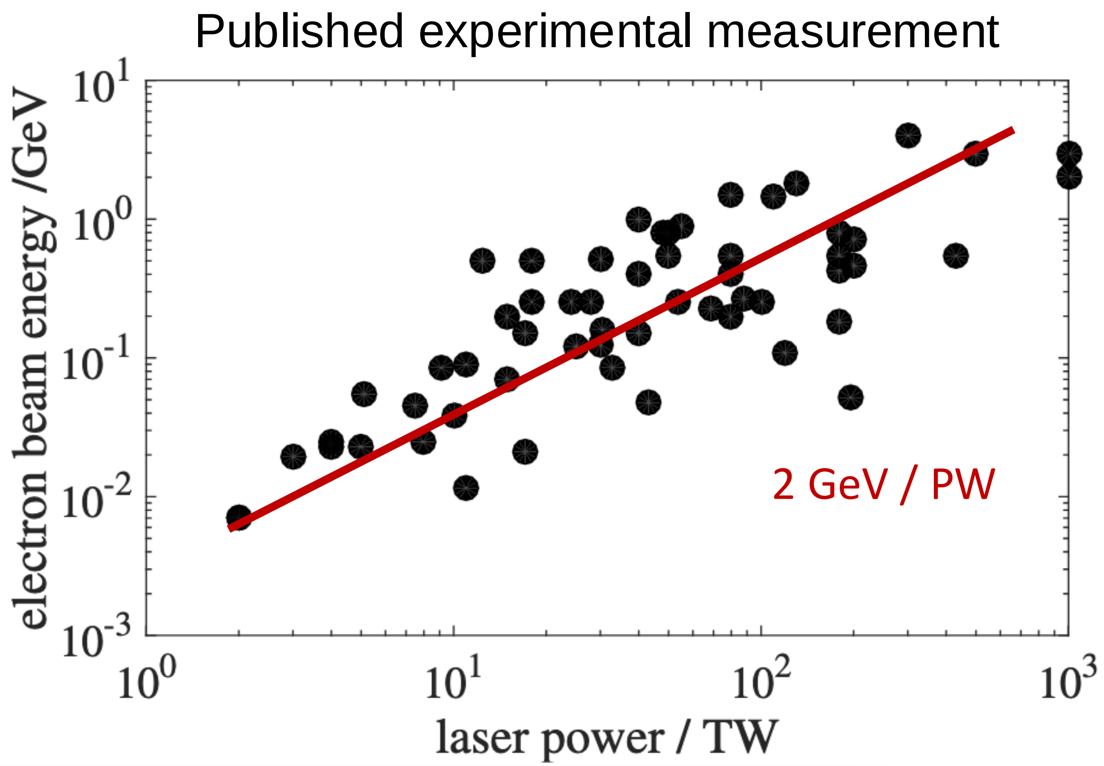
100 TV/m



?

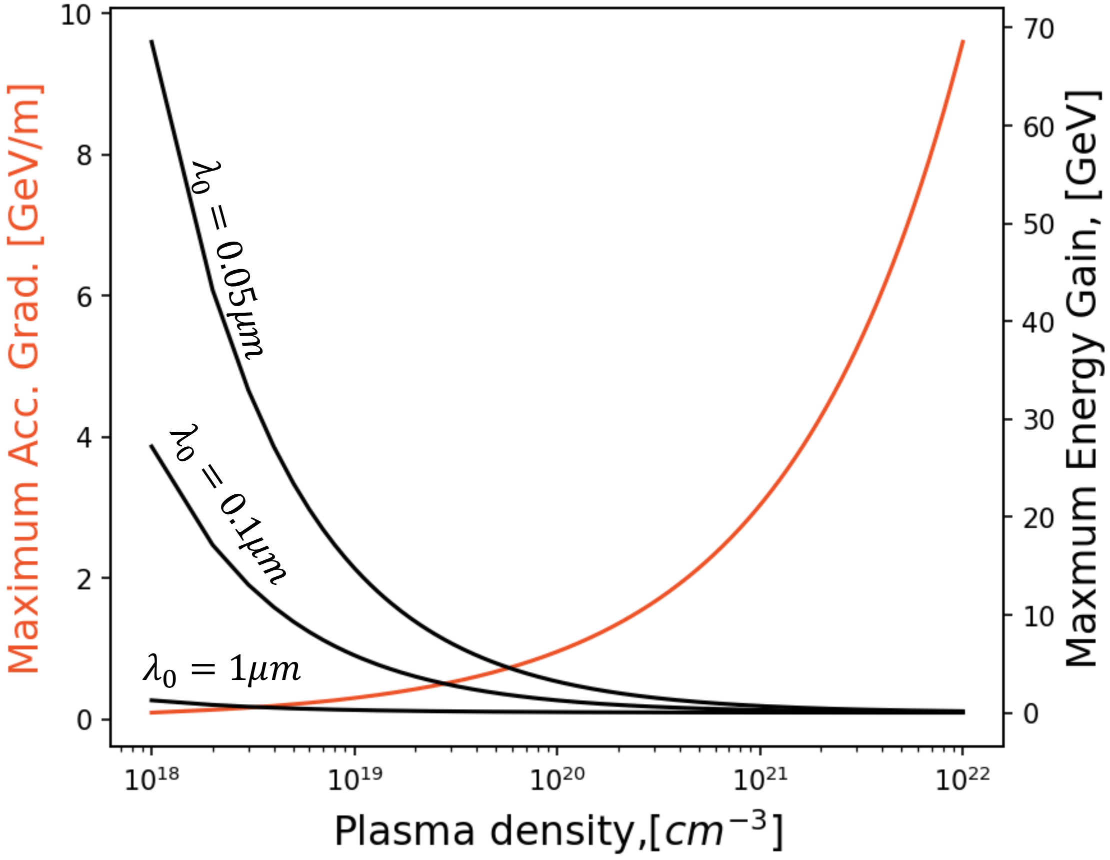
Energy Frontier of Plasma Accelerator





Scales with infinite laser power? -- > **NO,** due to bubble break!!

Role of Plasma Density



$$E_{wb}[GeV/m] = \frac{cm_e\omega_p}{e} \simeq 9.6\sqrt{n_p(cm^{-3})}$$

Dephasing

$$L_d[cm] \sim \frac{3.9}{\lambda_0^2[\mu m]n_p[10^{18}cm^{-3}]}$$

$$\Delta E[\mathrm{GeV}] \simeq 1.7\left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3}\left(\frac{10^{18}}{n_p[\mathrm{cm}^{-3}]}\right)^{2/3}\left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{4/3}$$

Guiding

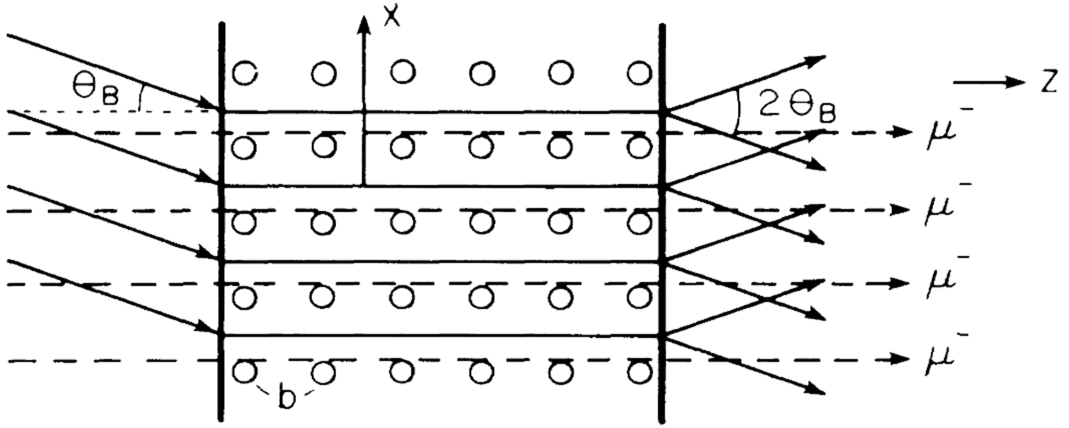
$$n_c = \frac{m_e c^2}{4\pi e^2 \lambda_0^2}$$

How wakefield can be generated in solid plasma $n_e > n_c$?
-- > short wavelength of laser -- > X-ray

bifeng.lei@liverpool.ac.uk

X-ray-driven Crystal Accelerator

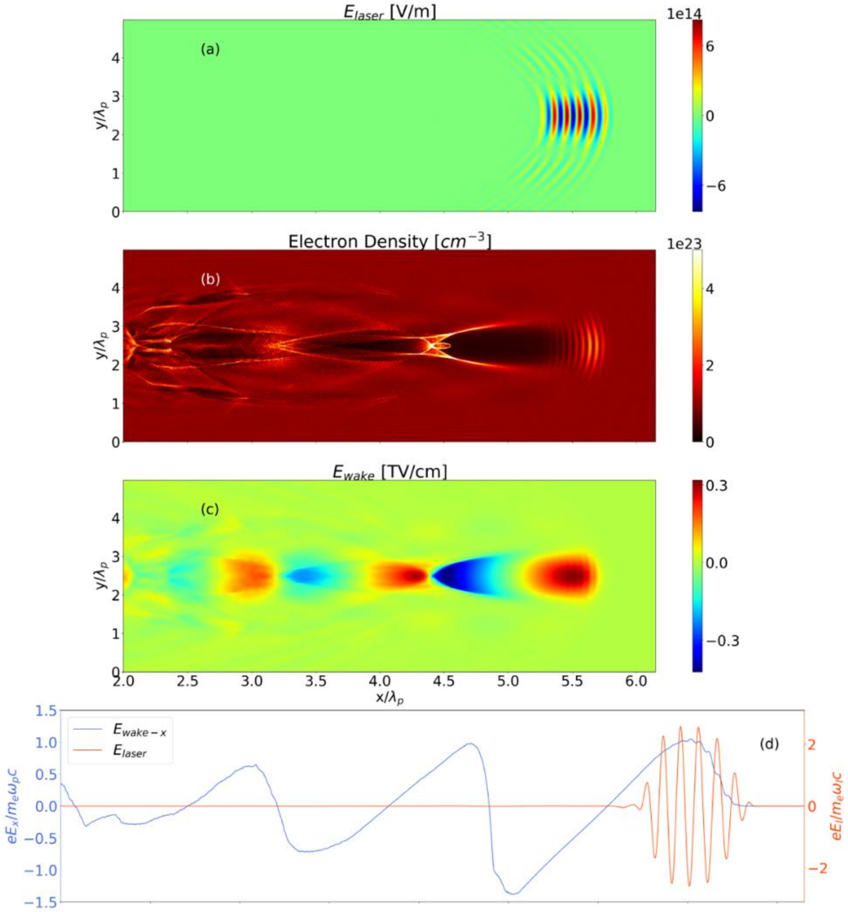
- Plasma density in Crystal: up to $10^{27} cm^{-3}$
- X-ray: $\lambda_0 = 1nm$ -- > $n_c = 1.11 \times 10^{27} cm^{-3}$ and $E_{WB} = 1\ PeV/m$



When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis can be accelerated.

@T. Tajima et al 1987

X-ray driven plasma wakefield in crystal



@Sahel, et al 2019

bifeng.lei@liverpool.ac.uk

Challenges and Future Research

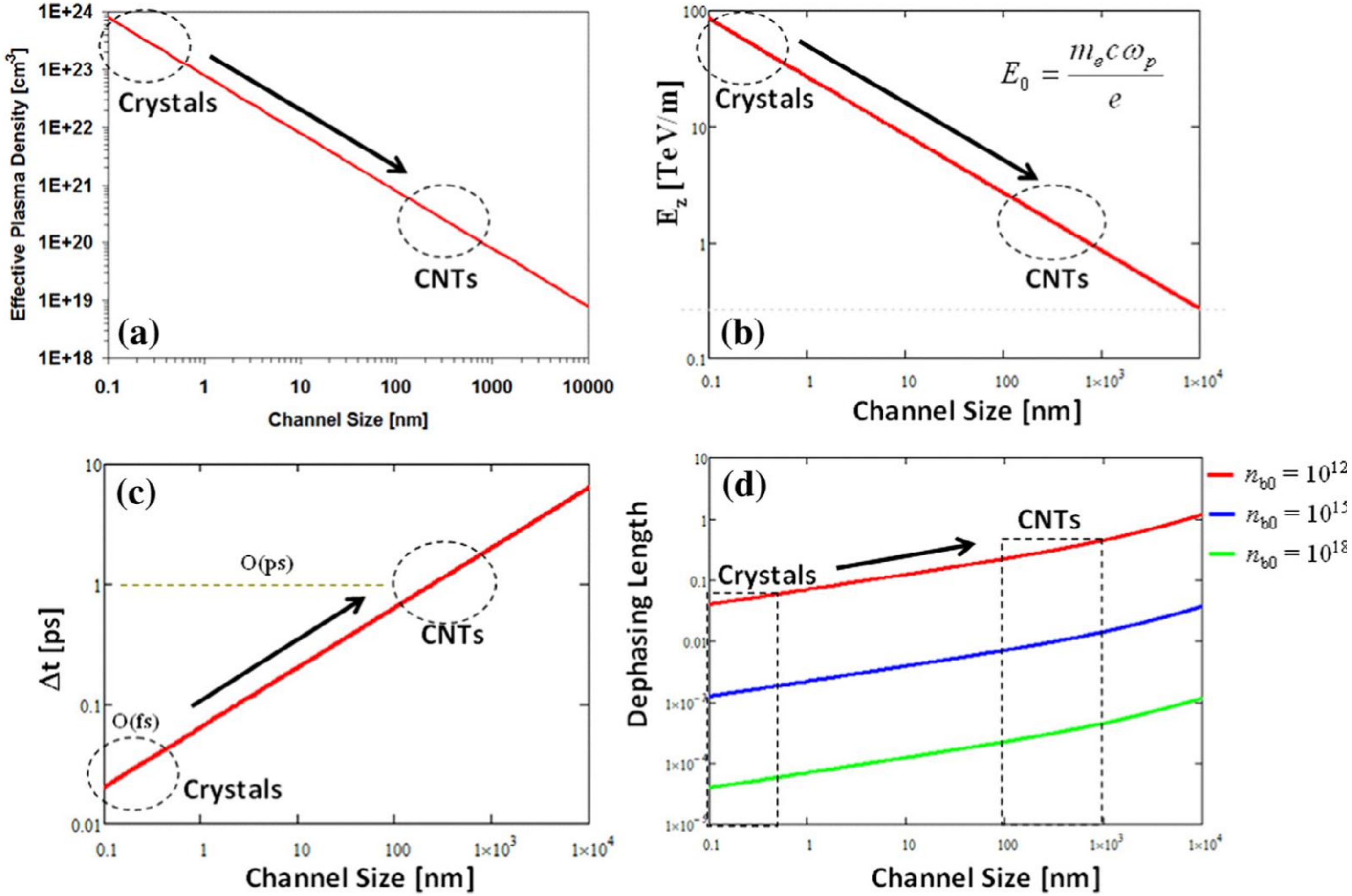
Open questions:

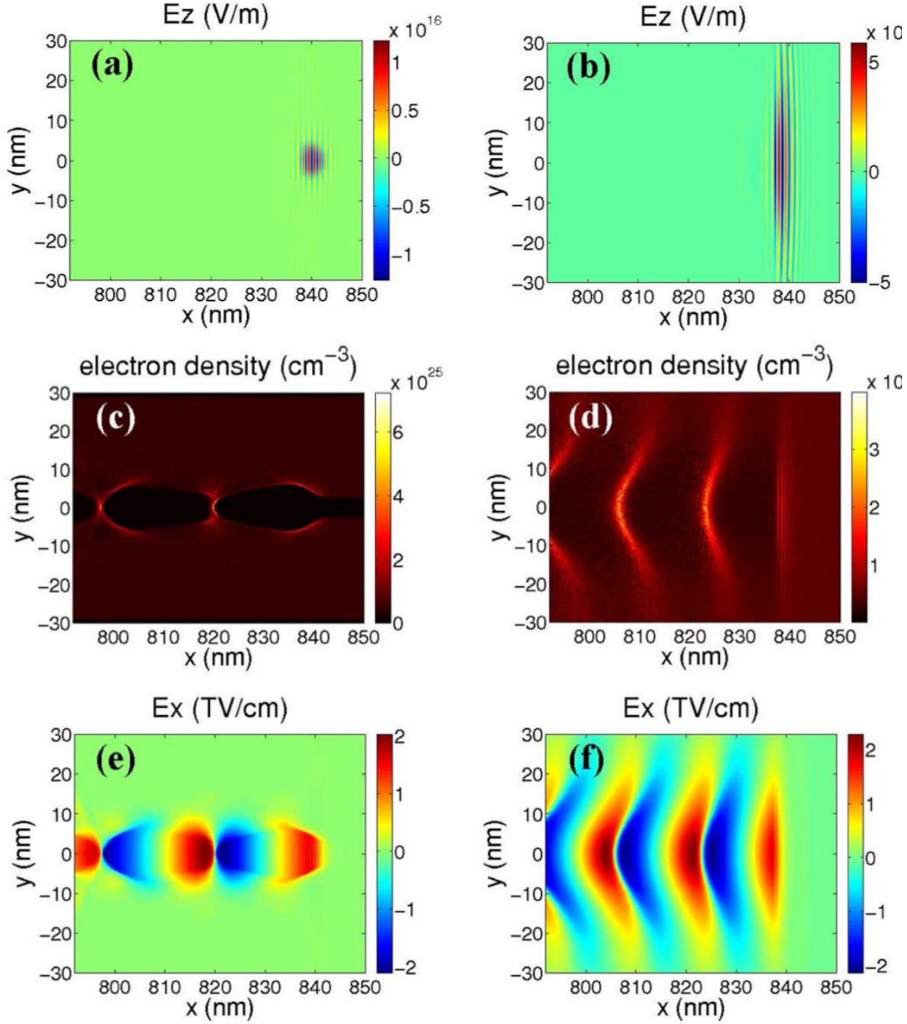
1. Material study: crystal damage and durability, ångströms-size limiting the acceleration volume and leads to fast dissociation
2. Availability of high intensity X-ray .
3. Complex particle and beam dynamics in crystal acceleration channels; Instabilities in crystal acceleration channels, such as filamentation/Weibel instability
4. Complex interaction of intense X-rays and crystalline structures
5. Practical Implementation: Transitioning from theoretical concepts to practical accelerator designs
6. Engineering challenges in crystal fabrication, beam handling, and detector systems need to be addressed.
7. …

Important topics:

1. Exploring different crystal materials and geometries.
2. Developing advanced X-ray optics and beam delivery systems.
3. Simulating and modelling the interaction processes, e.g. particle and beam dynamics in crystal acceleration channels instabilities in crystal acceleration channels, such as filamentation/Weibel instability ,
4. Investigating novel techniques for beam diagnostics and control.
5. …

Wakefield Excitation in Nano Structures

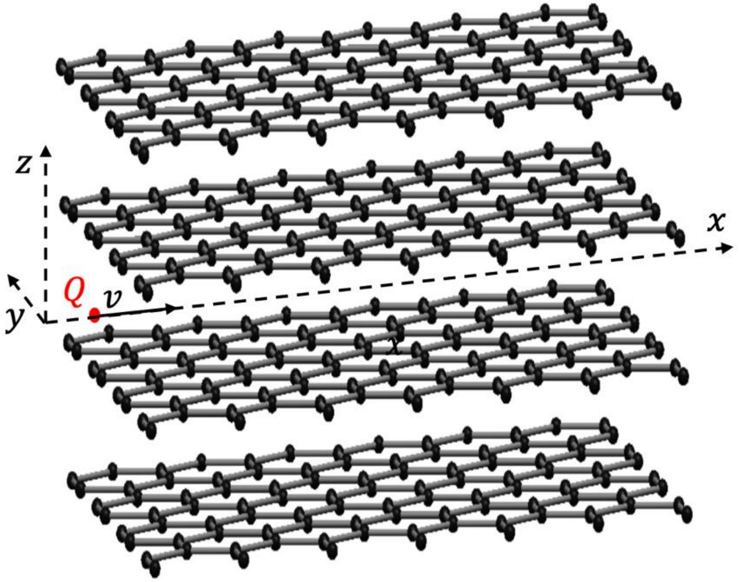


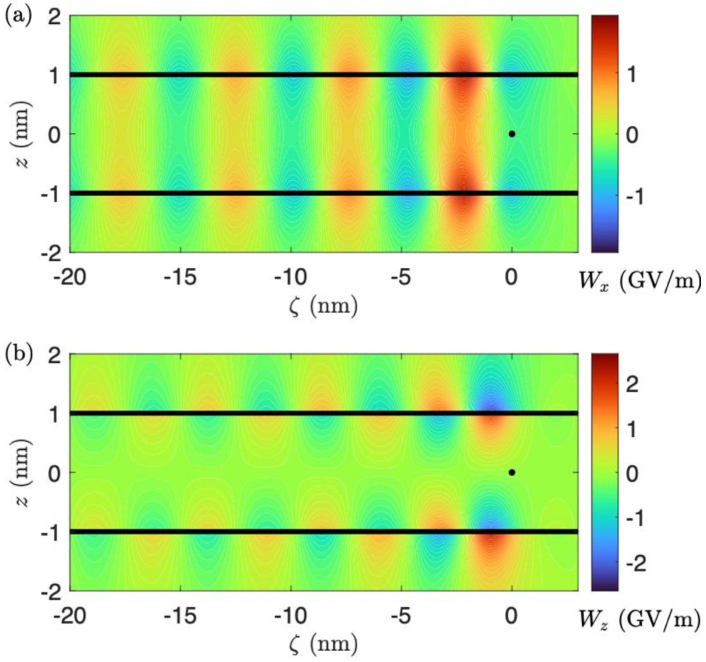


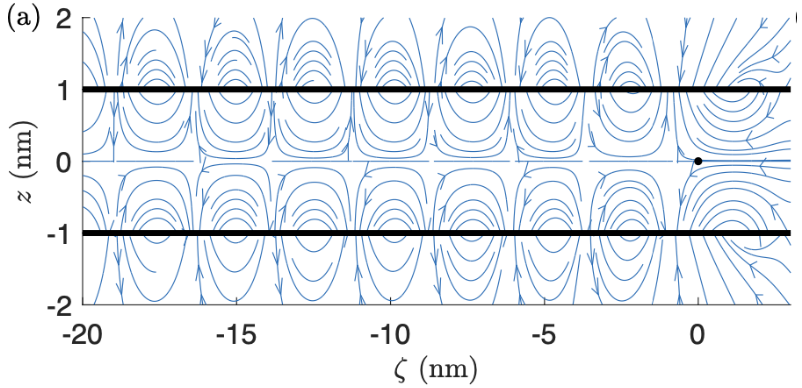
@Shin et al 2019

Wakefield in Graphene Layers: one particle model

@Martín et al. 2025







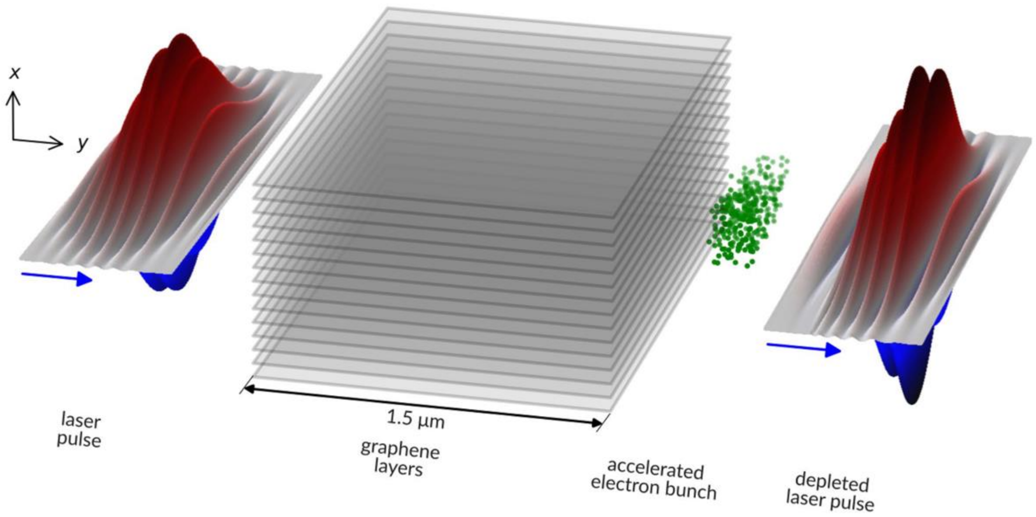
Continuity equation

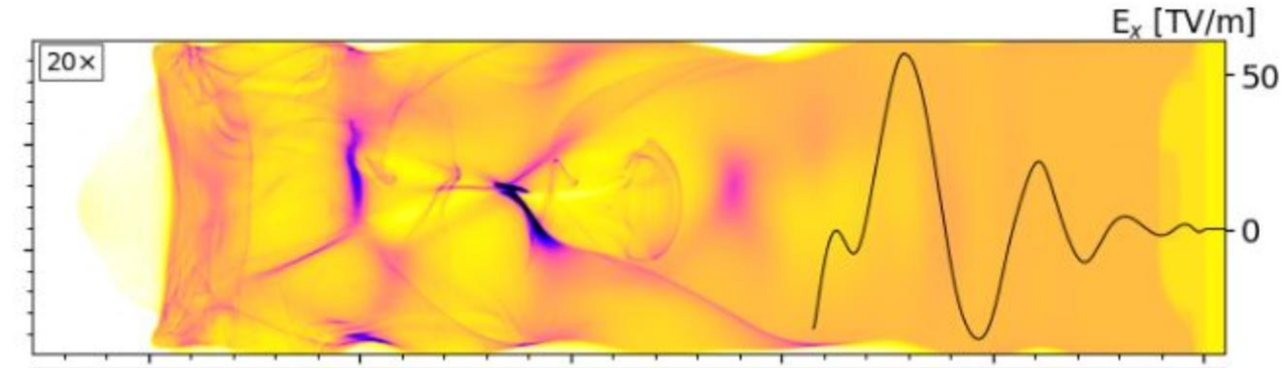
$$\frac{\partial n_j(\mathbf{r}_j,t)}{\partial t}+n_{0j}\nabla_j\cdot\mathbf{u}_j(\mathbf{r}_j,t)=0,$$

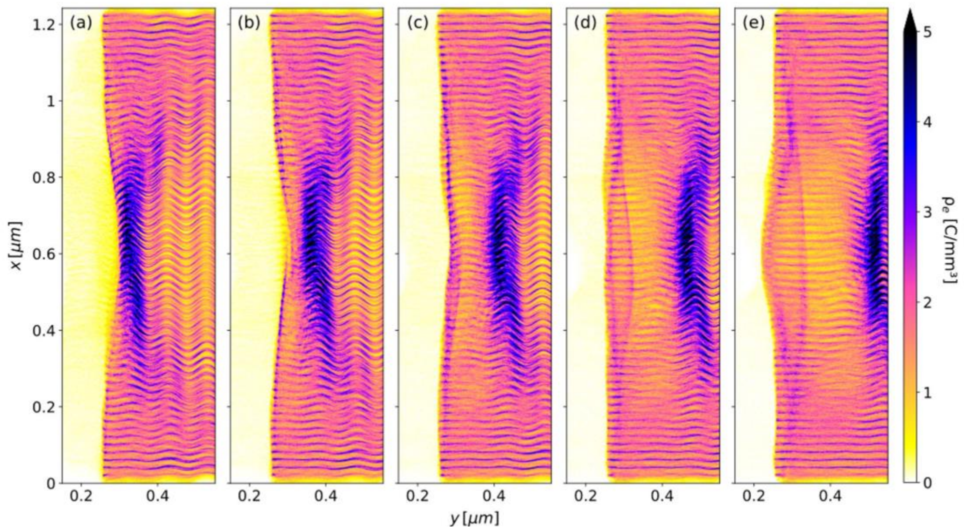
Momentum-balance equation of the electron fluid at each tube surface

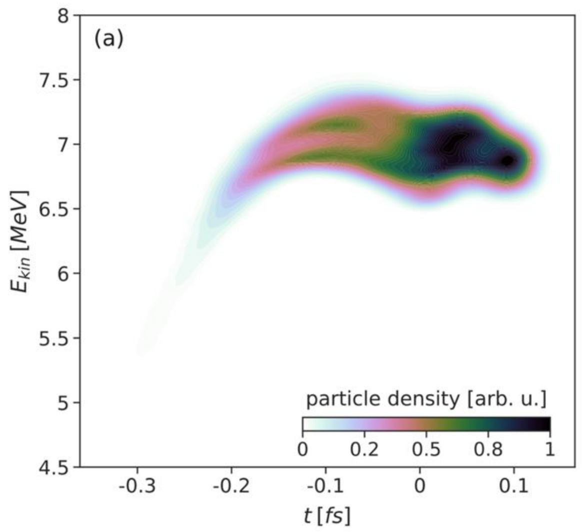
$$\frac{\partial \mathbf{u}_j(\mathbf{r}_j,t)}{\partial t}=\nabla_j\Phi(\mathbf{r}_j,t)-\frac{\alpha_j}{n_{0j}}\nabla_j n_j(\mathbf{r}_j,t)+\frac{\beta}{n_{0j}}\nabla_j\left[\nabla_j^2 n_j(\mathbf{r}_j,t)\right]-\gamma_j\mathbf{u}_j(\mathbf{r}_j,t),$$

Wakefield in Graphene Layers: Laser-driven





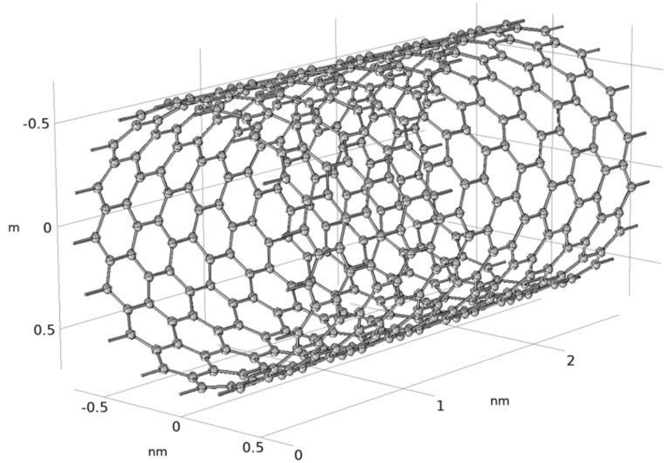


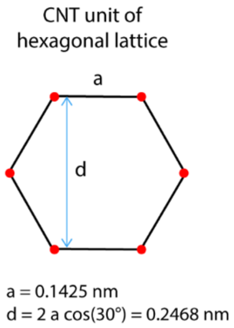


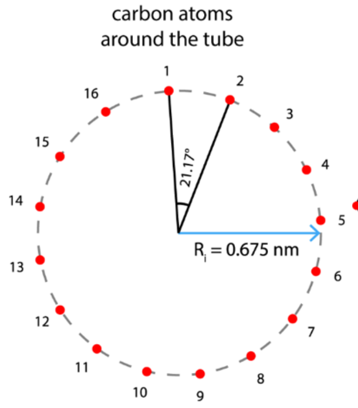
- Acceleration gradient: 4.79 TeV/m
- Self-injection at edge
- 0.4 fs-long bunch

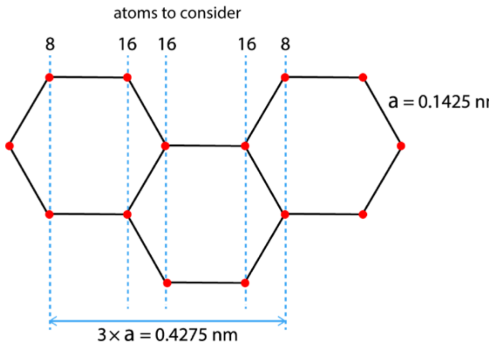
@ Cristian, et al, 2024

Metallic Carbon Nanotubes (CNTs): Armchair Type





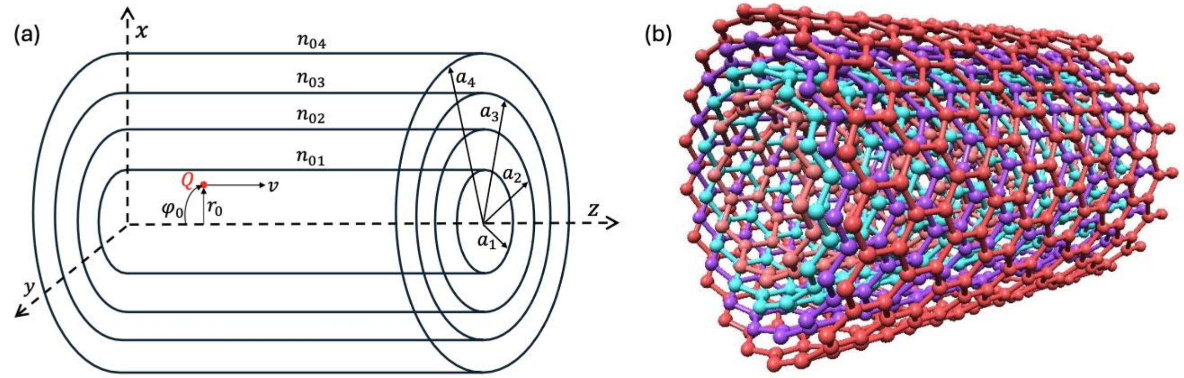




$$\rho = \frac{64\,\text{atoms}}{0.181\,\text{cm}^3} = 3.53 \times 10^{23}\,\text{atoms/cm}^3$$

Layer					Tube		
Number	Radius [nm]	Volume [nm³]	Atoms	Density [cm⁻³]	Volume [nm³]	Atoms	Density [cm⁻³]
1	0.675	0.181	64	3.530×10^{23}	N/A	64	N/A
2	1.115	0.299	108	3.606×10^{23}	1.058	172	1.626×10^{23}
3	1.555	0.418	152	3.639×10^{23}	2.636	324	1.229×10^{23}
4	1.995	0.536	196	3.658×10^{23}	4.733	520	1.099×10^{23}
5	2.435	0.654	240	3.669×10^{23}	7.351	760	1.034×10^{23}
6	2.875	0.772	288	3.729×10^{23}	10.489	1048	9.991×10^{22}
7	3.315	0.890	332	3.729×10^{23}	14.147	1380	9.755×10^{22}
8	3.755	1.009	376	3.728×10^{23}	18.325	1756	9.583×10^{22}
9	4.195	1.127	420	3.727×10^{23}	23.023	2176	9.452×10^{22}
10	4.635	1.245	464	3.727×10^{23}	28.241	2640	9.348×10^{22}
...	...	...	...	...	...	...	...
45	20.035	5.382	2036	3.783×10^{23}	538.482	47184	8.762×10^{22}

Plasma Wakefield in CNT Tube

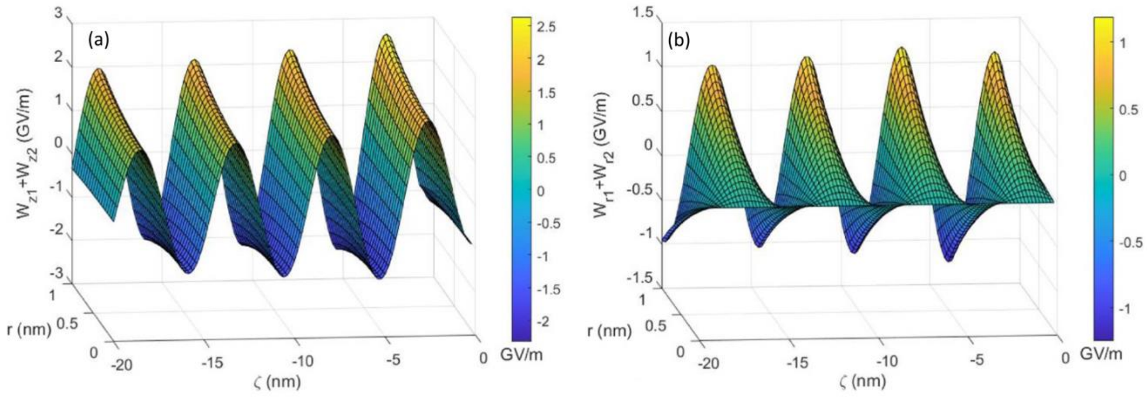


$$\frac{\partial n_j(\mathbf{r}_j,t)}{\partial t} + n_{0j}\nabla_j \cdot \mathbf{u}_j(\mathbf{r}_j,t) = 0,$$

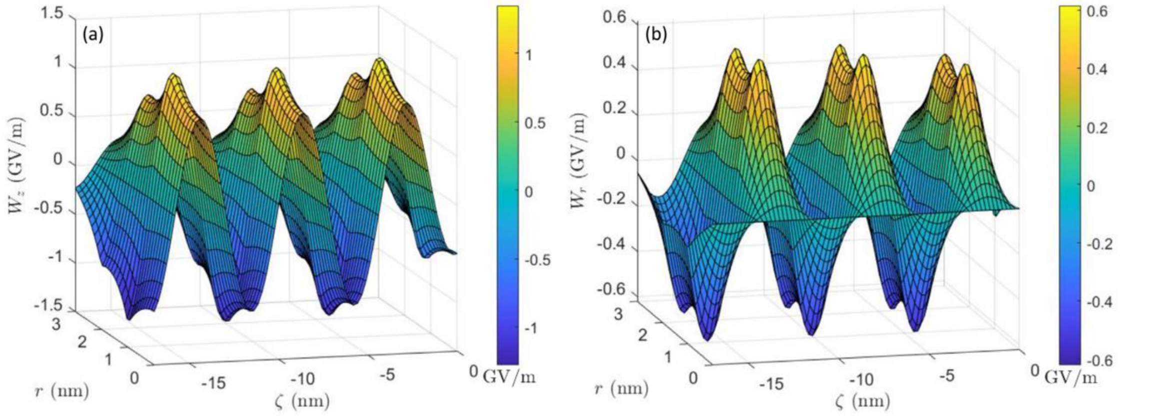
$$\frac{\partial \mathbf{u}_j(\mathbf{r}_j,t)}{\partial t} = \nabla_j \Phi(\mathbf{r}_j,t) - \frac{\alpha_j}{n_{0j}}\nabla_j n_j(\mathbf{r}_j,t) + \frac{\beta}{n_{0j}}\nabla_j\left[\nabla_j^2 n_j(\mathbf{r}_j,t)\right] - \gamma_j \mathbf{u}_j(\mathbf{r}_j,t),$$

@ Palo et al 2025

SWCNT

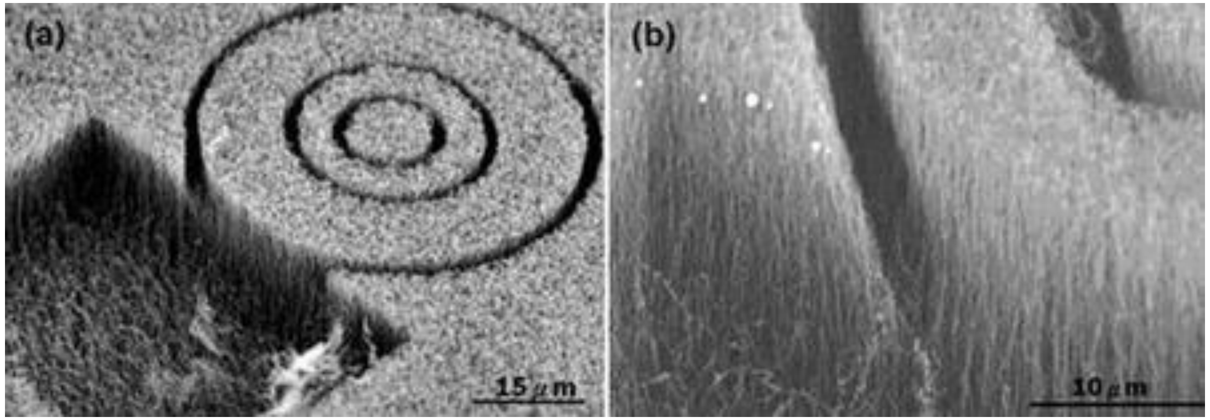


DWCNT

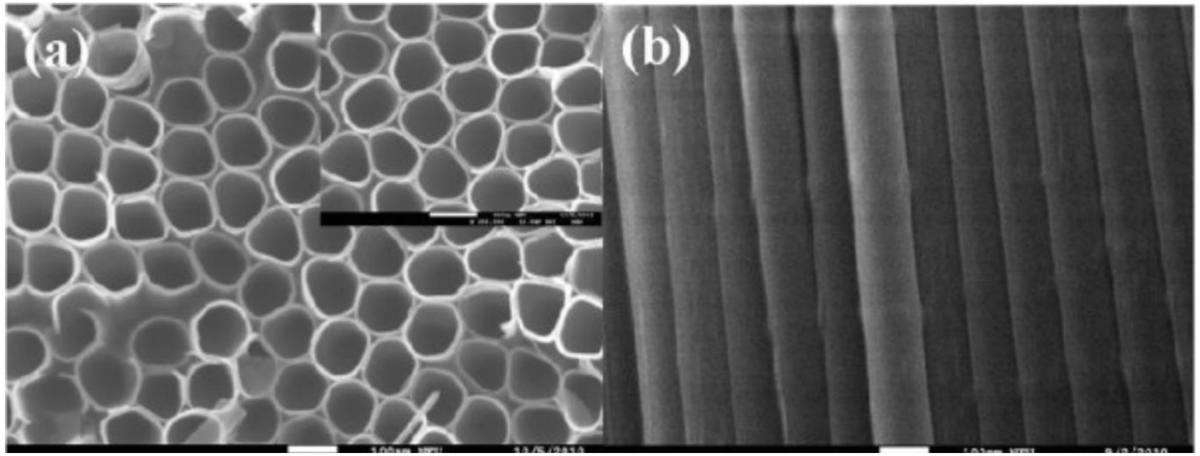


Nano-structured CNTs: CNTs in dense forest form

@Hung et al APL 91, 093121 (2017)

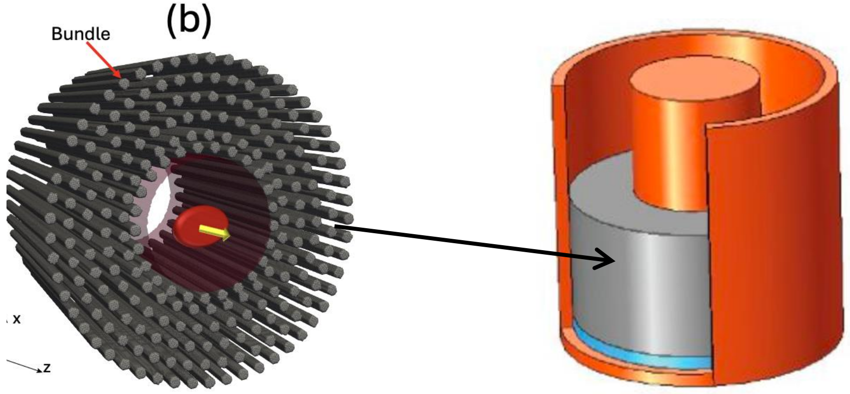


@Teen et al nano express, 579 (2012)

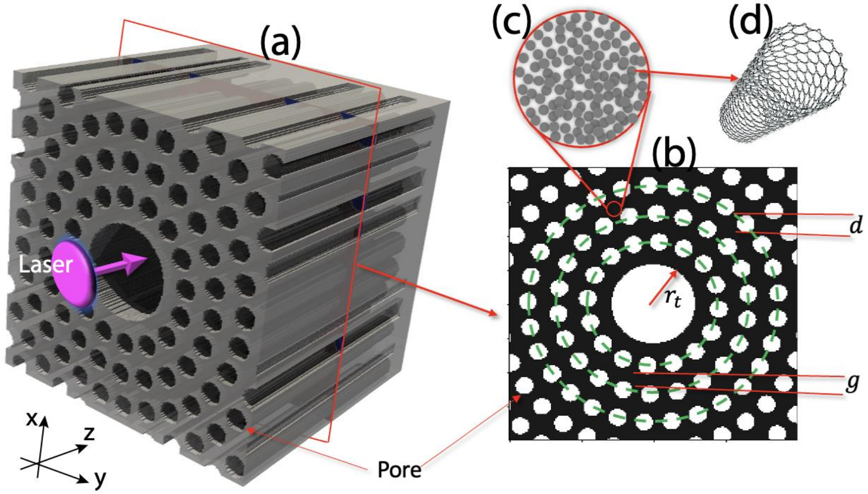


CNT bundle

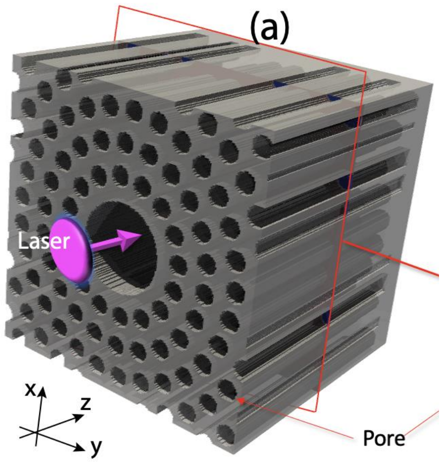
Target former

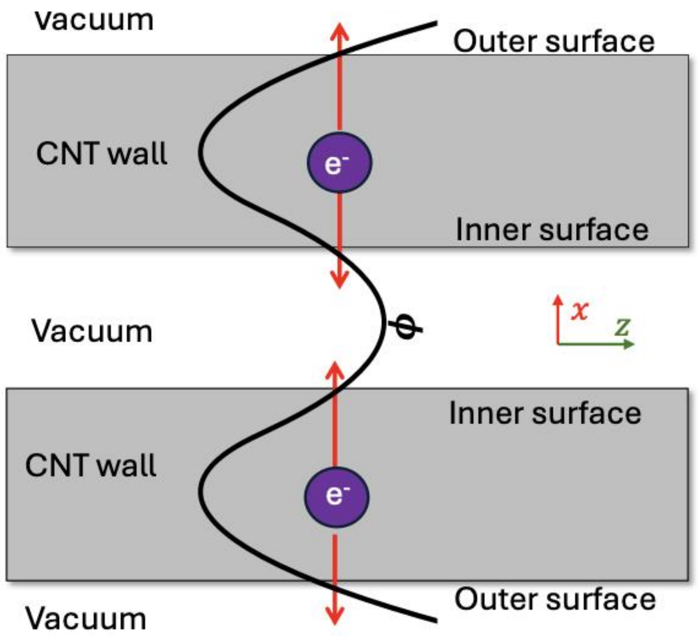


CNT porous



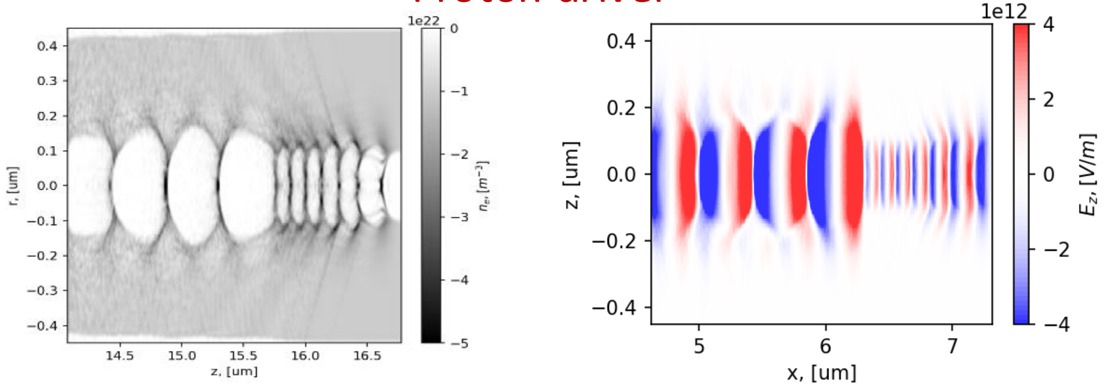
Plasma Wakefield in Structured CNT Forest



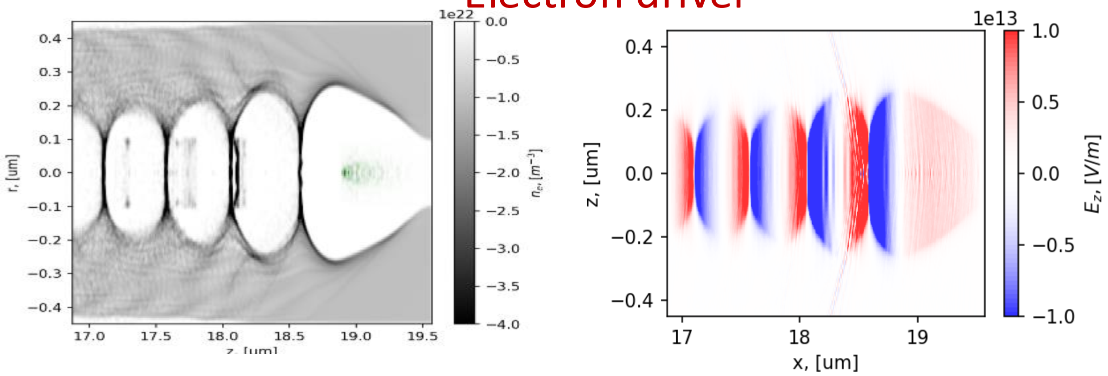


@B.Lei et al 2025

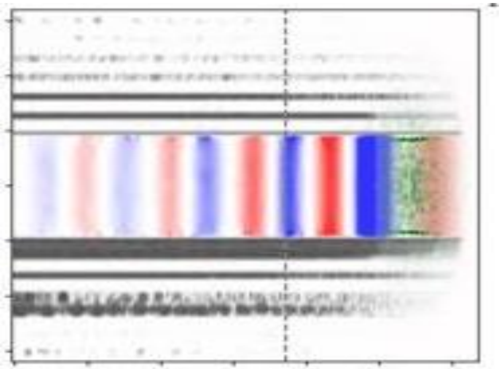
Proton driver



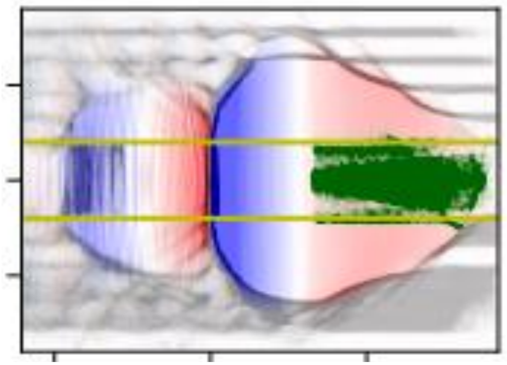
Electron driver



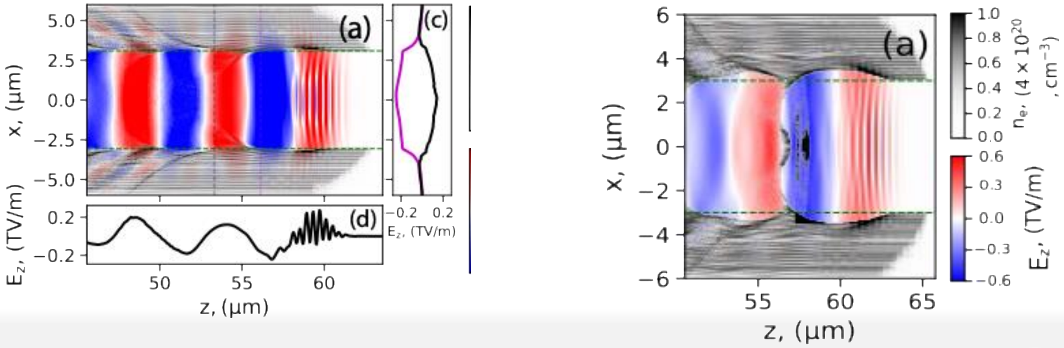
Surface plasmon



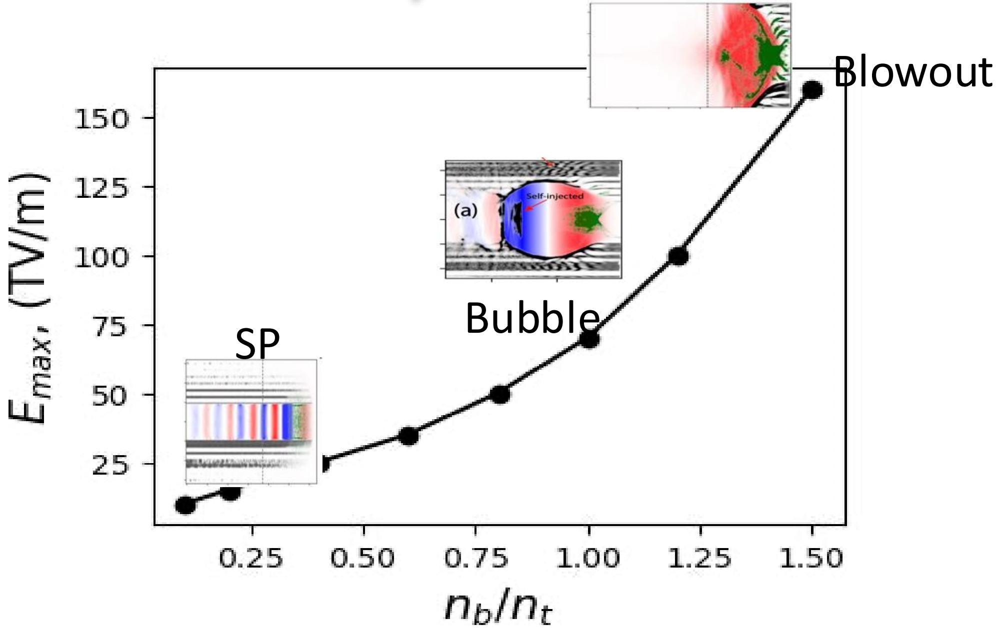
Plasma bubble

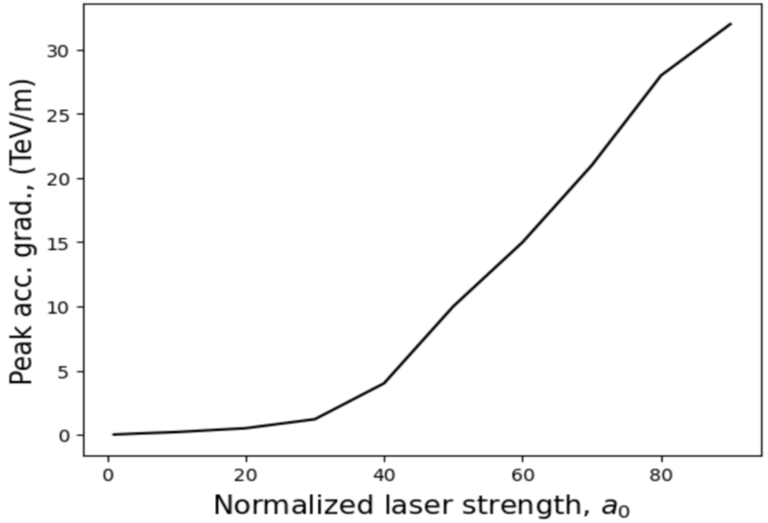


Laser driver

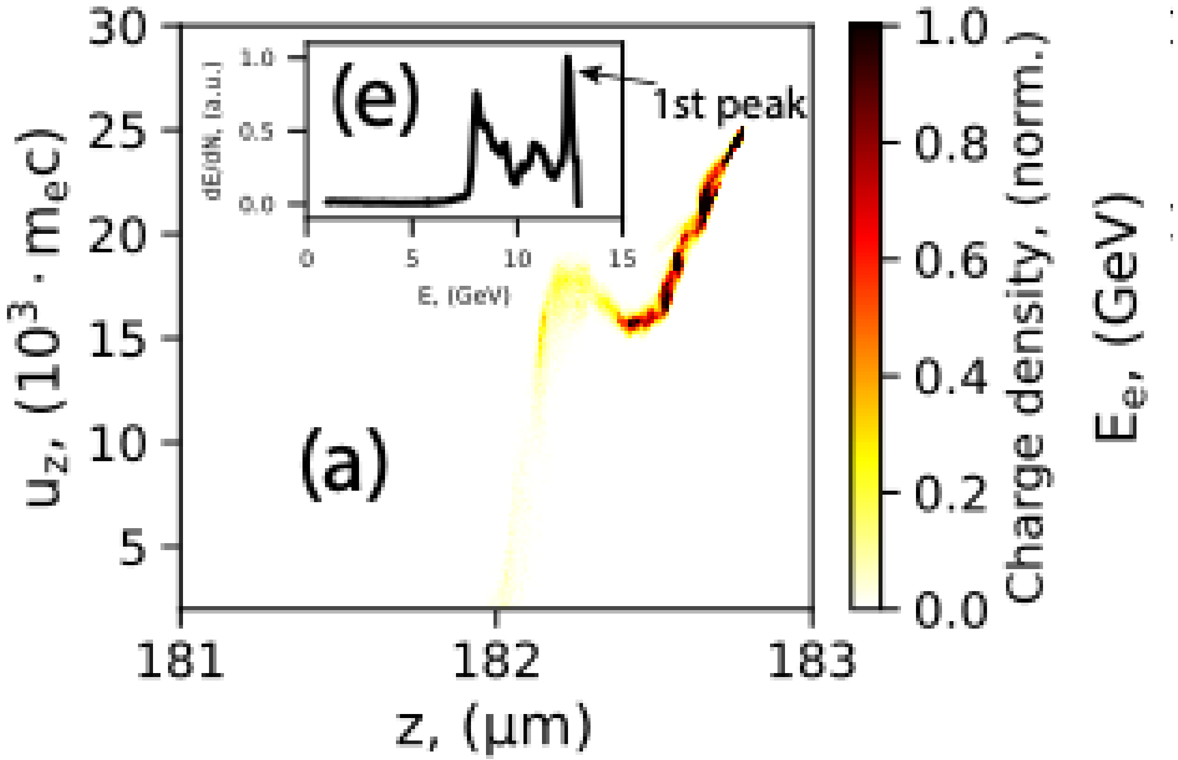


100s TeV/m Acceleration Gradient Achievable





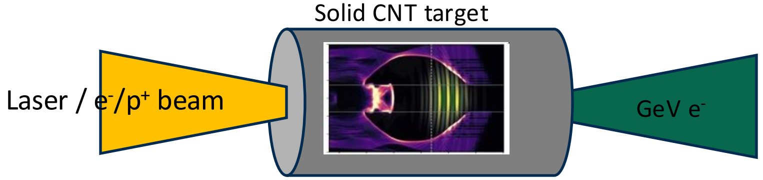
$$n_p = 2 \times 10^{22} cm^{-3}, \frac{n_b}{n_t} = 0.5$$



$G \simeq 100\, TeV/m$

@B.Lei et al 2025

Potential Drivers: Particle Beams



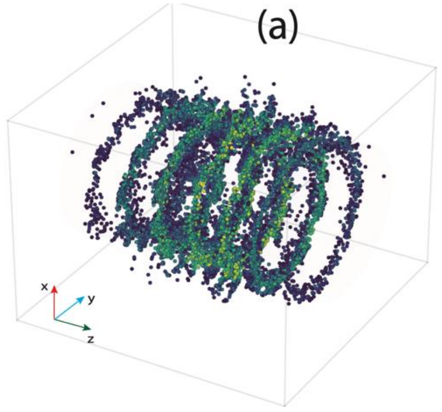
	Unit	FACET-II e^- beam	FACET-II e^+ beam	CLARA e^- beam	NPQED Collider e^- beam	CERN p^+ beam
Energy	GeV	10 [4.0-13.5]	10 [13GeV]	0.25	125	400
Charge	nC	2 [0.5-5]	1	0.25 [0.02-0.25]	0.14-1.4	48
Norm. emitt._x,y	um-rad	4.4, 3.2 [3-6]	3	<1		3.5
Peak current	kA	300	20	1-3	1700	0.16
Beam size x	um	3	3	10	0.01	10
Beam size y	um	2	2	10	0.01	10
Beam size z	um	0.48	0.48	9/30	0.01-0.1	6-12 cm
Max. beam density	Cm-3	1e22	1e22	1e18	1e34	1e14
Min. energy spread	%	1.4 [0.4-1.6]	0.1	0.01-0.06	0.1	0.01
Peak electric field	TV/m	3.2			4500	

	Unit	100TW FEBE@STFC	200TW laser@HIJ	VEGE@CLPU
Intensity	W/cm2	$>1 \times 10^{20}$	$>3.5 \times 10^{21}$	1×10^{20}
Peak Power	TW	120	>200	200 [1 PW]
Wavelength	nm	800	800	800
Max. strength	/	2	7	10
On-target energy	J		4	2
Beam size Focus, x	um	30	6	8
Beam size Focus, y	um	30	6	8
Beam size Duration, z	fs	<40fs	17	25
Temporal contrast	/	10^{-13}	10^{-12}	10^{-13}

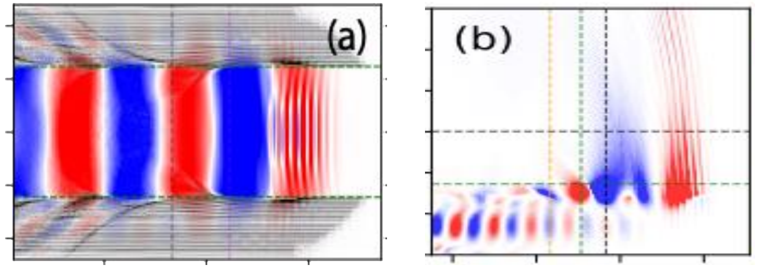
@PRL. 122, 190404 (2019)

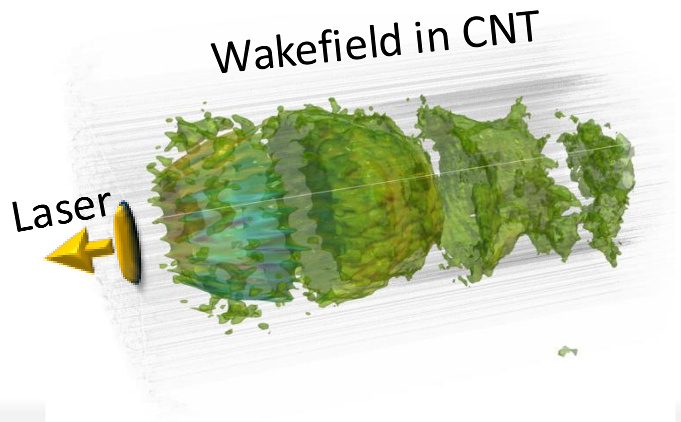
Challenges and Future Research

- Theoretical modelling of the complex dynamics of laser-crystal interaction
- Geometrical study of surface plasmon and wakefield excitation
- Target fabrication, controllability and flexibility.
- New simulation capabilities of multi-physics: plasma, crystal lattice, radiation and QED
- Preparation of high density particle beam as drivers, $n_b > 10^{20} cm^{-3}$
- Practical application in particle acceleration, radiation generation, strong field generation, astrophysics, etc.
- New diagnostic technologies required to understand the ultrafast plasma dynamics in crystal
- Experimental demonstration are demanded for proof of principle: CLPU laser, FEBE, ELI-beamlines, Jeti200, FACET-II, X-ray@LCLS-II/XFEL, Proton beam@CERN, etc.



Cylindrical VS. Flat





Thank you for your attention!

Any questions?