LLNL-ILE Seminar (July 12, 2022)

High Density Laser Wakefield Accelerator(LWFA)

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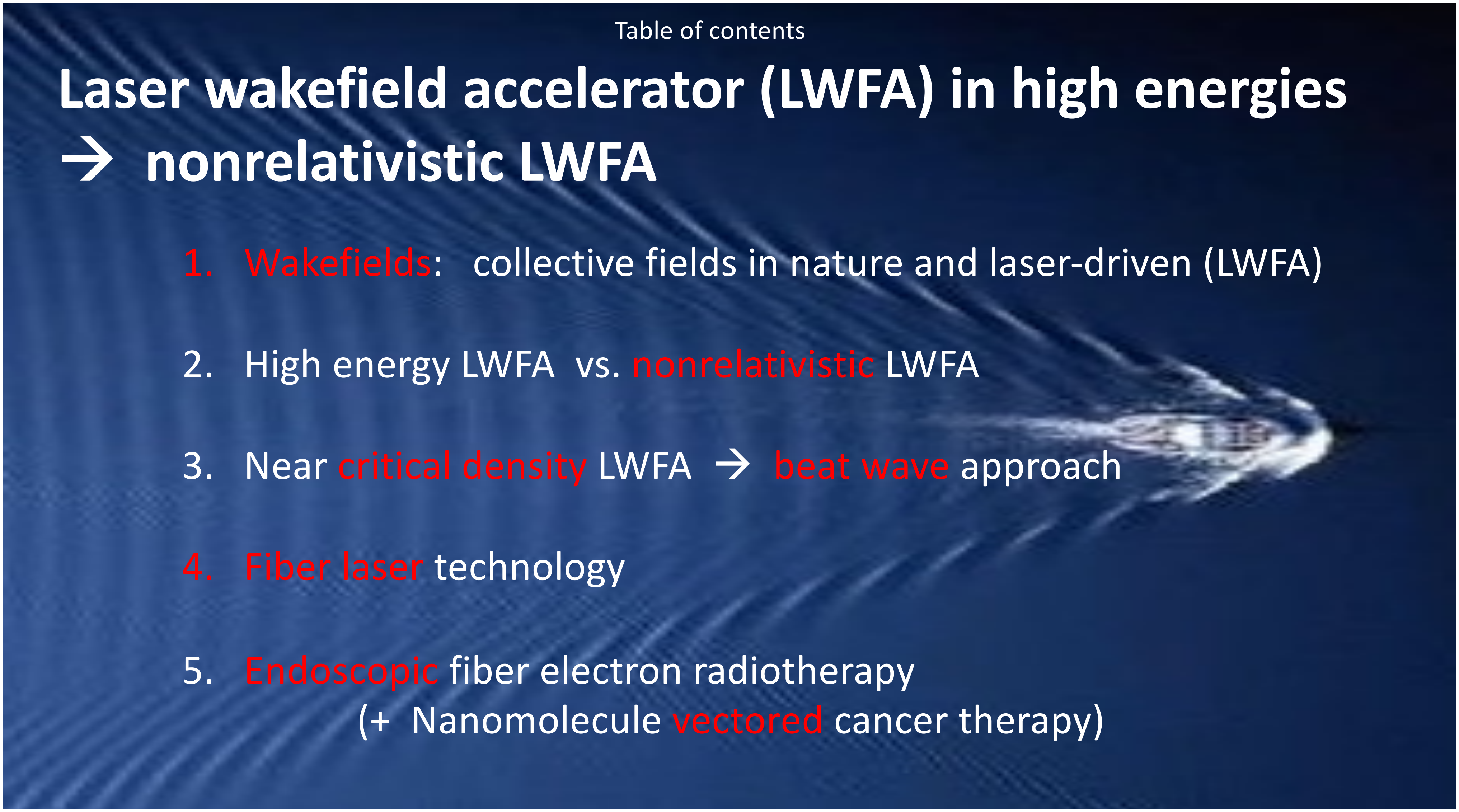

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Laser wakefield accelerator (LWFA) in high energies → nonrelativistic LWFA

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2. High energy LWFA vs. nonrelativistic LWFA
3. Near critical density LWFA → beat wave approach
4. Fiber laser technology
5. Endoscopic fiber electron radiotherapy
   (+ Nanomolecule vectored cancer therapy)

Wake acceleration

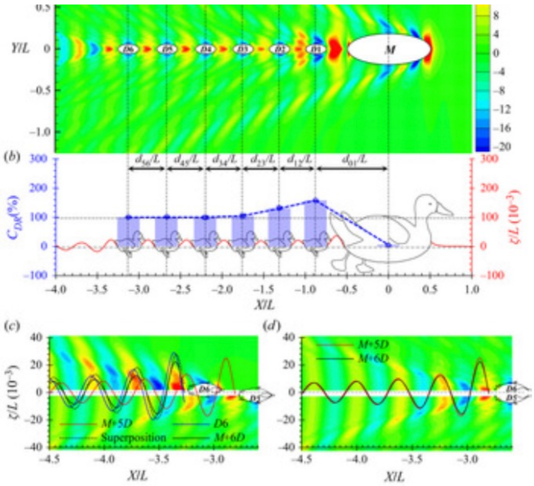
Bow and stern wakes

Nature (or mother duck) shows us.

[東大の学生時代の通学で、上野不忍池を通る時に
鴨の後ろにできる波、航跡を眺めて、この波のなす
不思議に啓発され、こうした現象に引き込まれた (1968)]

→ Rostoker’s collective acceleration (1973)

→ Tajima-Dawson’s wakefield acceleration (1979)

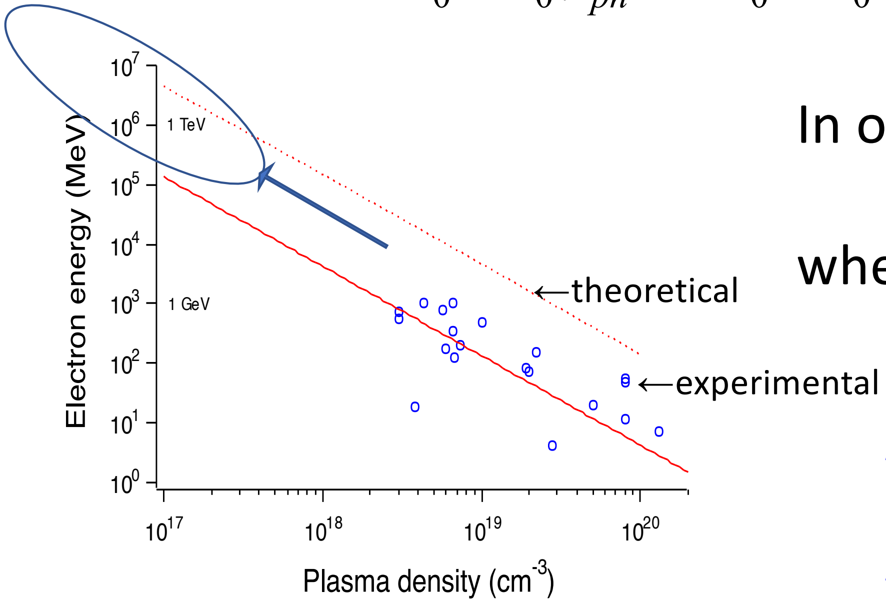


Yuan et al. JFM (2021)

Theory of wakefield toward extreme energy

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

(when 1D theory applies
Tajima / Dawson, 1979)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = [n_{cr}(\omega) / n_e]^{1/2}$$

n_{cr} =10^{21}/cc (1eV photon)
$\longrightarrow$ 10^{29} (10keV photon)
n_e = 10^{16} (gas) $\longrightarrow$ 10^{21}/cc(porous solid)

$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length

$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

pump depletion length

Demonstration (1994), realization, and applications of laser wakefield accelerators

30 September 2004

International weekly journal of science

nature

www.naturejpn.com

Dream beam

The dawn of compact particle accelerators

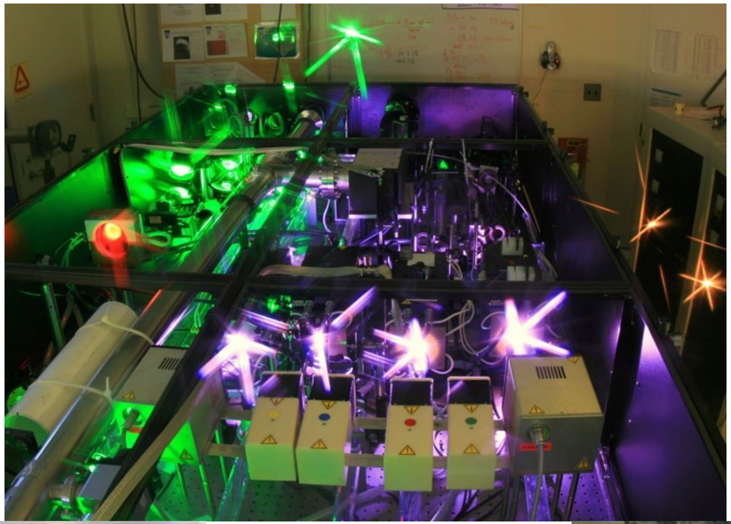
Offshore tuna ranches
A threat to US waters?

The Earth's hum
Sounds of air and sea

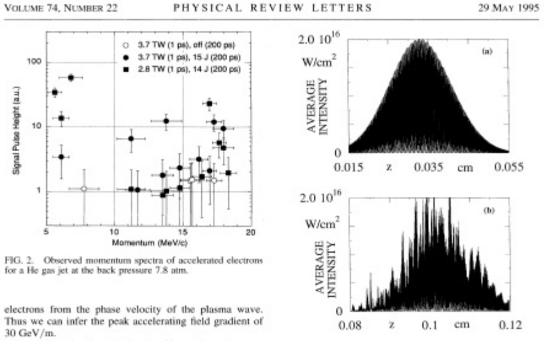
Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

(2004)



(Michigan)



VOLUME 74, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 1995

FIG. 2. Observed momentum spectra of accelerated electrons for a He gas jet at the back pressure 7.8 atm.

electrons from the phase velocity of the plasma wave. Thus we can infer the peak accelerating field gradient of 30 GeV/m.

Nakajima, et al (1994, 1995)

Using ILE laser

4 GeV laser accelerator LBL

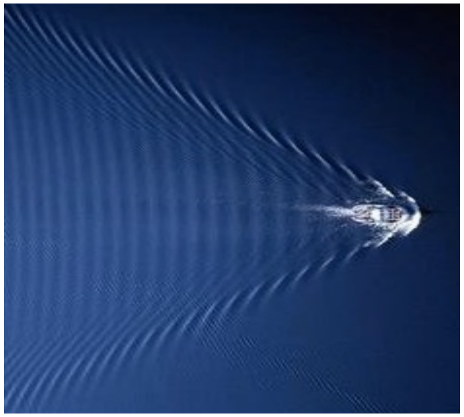
←

3GeV Synchrotron SOLEIL

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed
maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0,
causes **easier trapping** and **acceleration of more #**



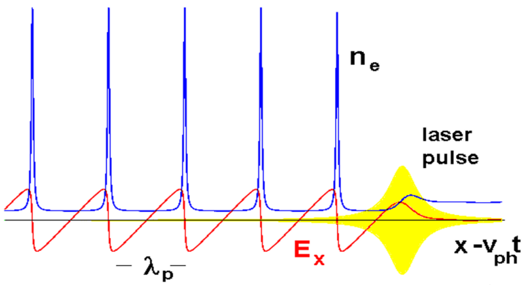
vs

With low phase velocity
More particle trapping

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph}/e$

No wave breaks and wake peaks at v≈c

Multiple of waves at $v < c$



← relativity regularizes
(*relativistic coherence*)

$a_0 \sim 10 >> 1$ (relativistic wave)

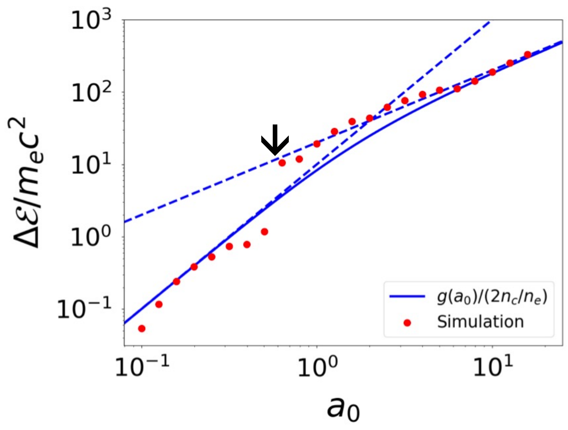
Tajima-Dawson field $E = m\omega_p c/e$ (~ GeV/cm)

Transition to near-critical density $n_e \sim n_{cr}$
Transition to $a_0 < 1$ regime

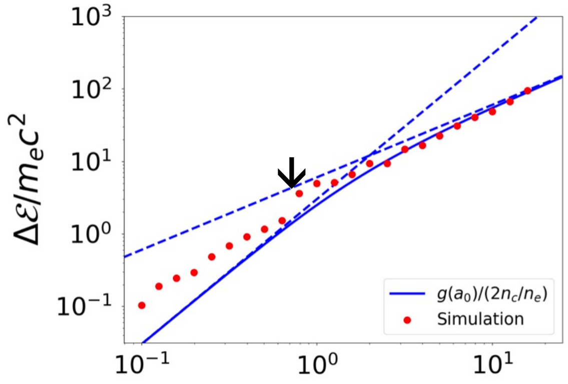
v_g (group velocity of photon) = v_p (phase velocity of plasma wave) $\ll c$

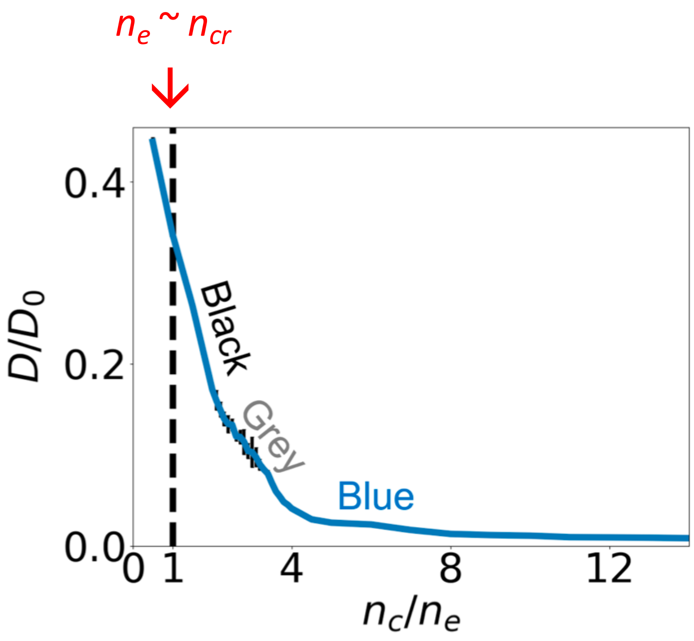
v_{tr} = sqrt (eE / mk) (trapping width), self-injection easy

Energy gain

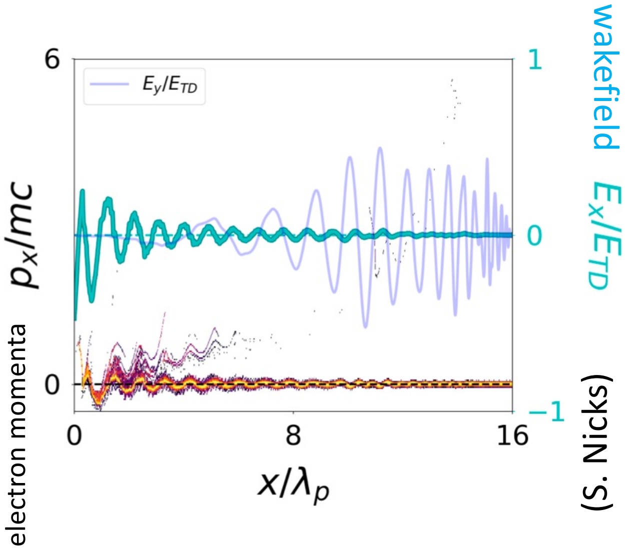


(a) E_{max} vs a_0 for fixed density ratio of 10





D ~ specific entropy / efficiency of coupling



(S. Nicks)

Laser Wakefield Acceleration near critical density

Near critical density ~ $n_e = 10^{21}$ /cc

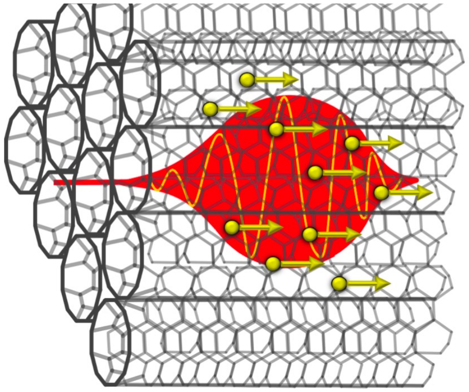
gaseous plasma → solid nanotube

Excitation of electron acceleration possible with $I \sim 10^{14}$ W / cm^3

Coupling gets stronger near $n_e = 10^{21}$ /cc

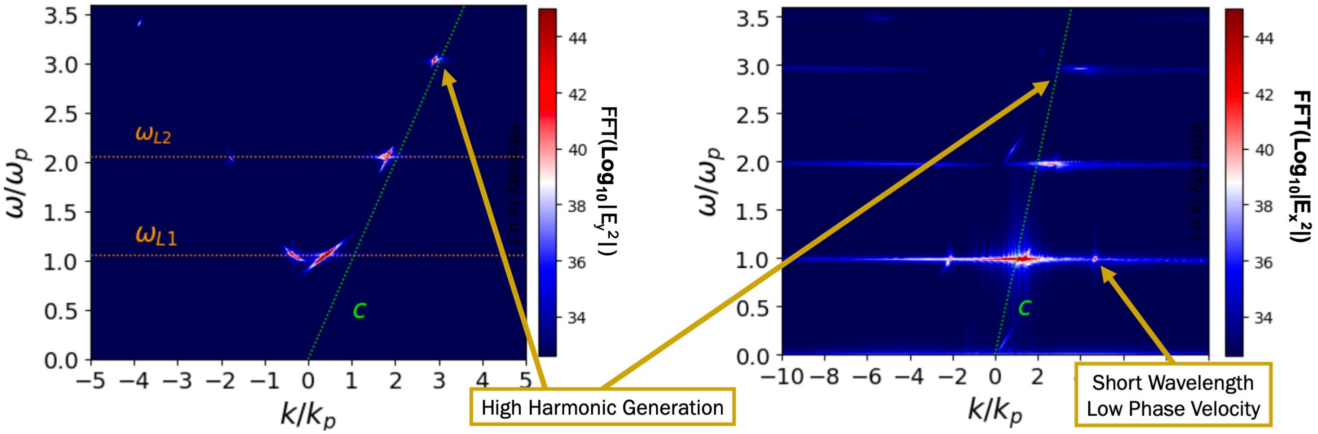
←overlap of plasma waves with different v_p

← curved laser $\omega\,(k)$, varied v_g



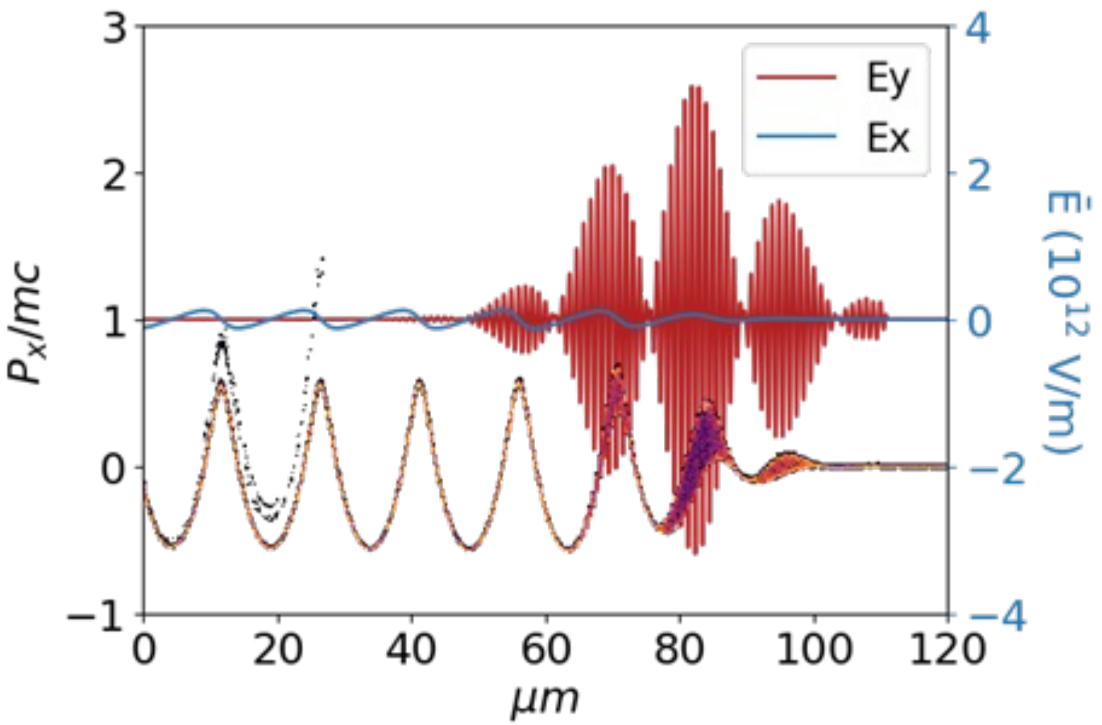
Dispersion Relation: FFT(Log$_{10}$E)

- High Harmonic Generation
- Short Wavelength and Low Phase Velocity Electrostatic Waves allow for more efficient particle acceleration



Laser **beat wave** excitation of wakefield

Beat of two lasers ($\omega_0\ k_0$) (ω_1, k_1) to match with the plasma eigenmode ($\omega_p, k_0 - k_1$), → wakefield



laser

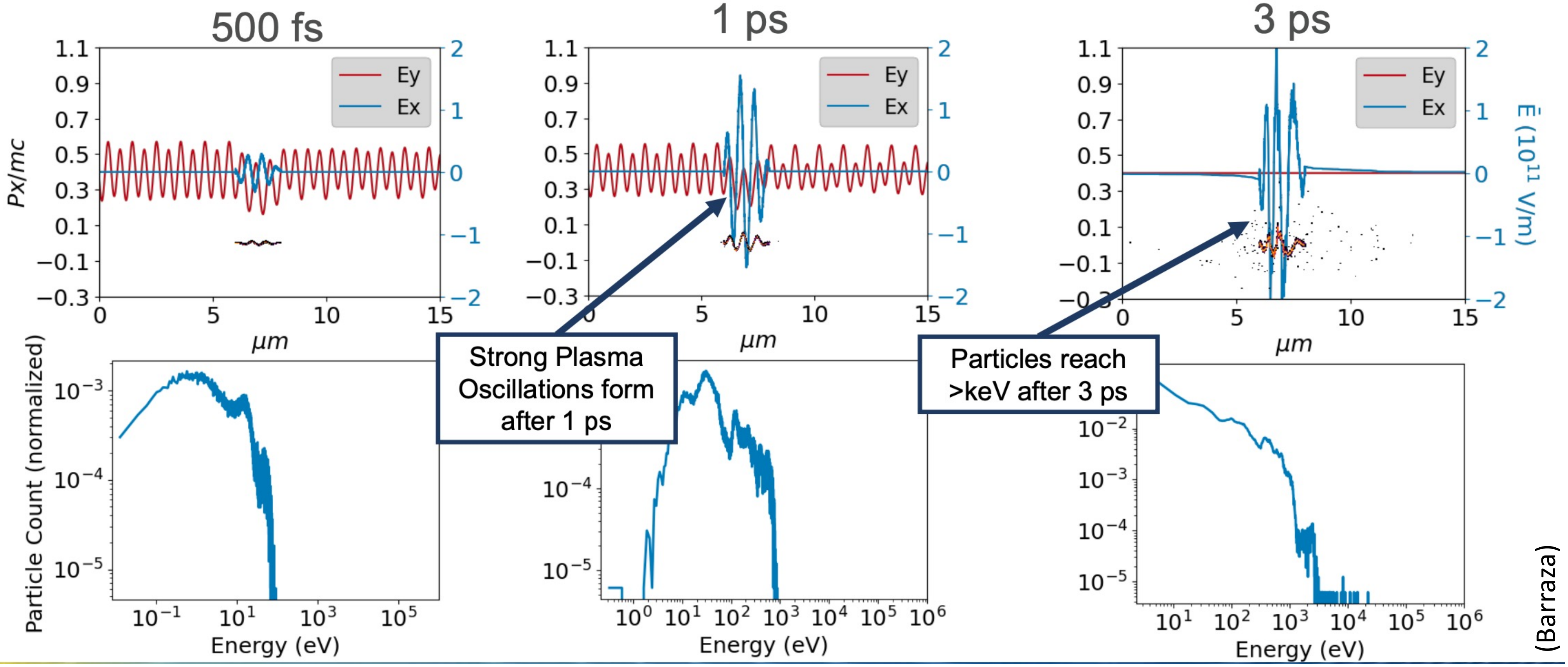
$$v_{ph} = \frac{\omega_p}{k_p} = \frac{\omega_0 - \omega_1}{k_0 - k_1} \qquad v_g = \frac{\partial\omega}{\partial k} = \frac{c}{\blacksquare}\sqrt{1 - n_e/n_c}$$

wakefield energy gain

(Nonrelativistic limit of energy gain by single pulsed EM wave [NB: beat wave can enhance this; also there are more subtle density dependences near critical density])

$$W_{max} = (pi/2)\, mc^2\ (\omega_0\ /\ \omega_p)$$

Target Foil Simulations in time: $a_0 = 0.007 \rightarrow 10^{14} W/cm^2$ with 2 µm Target



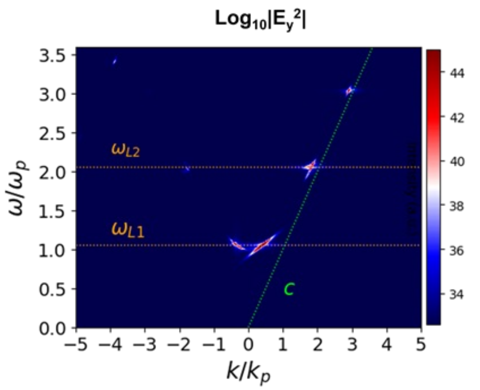
Strong Plasma Oscillations form after 1 ps

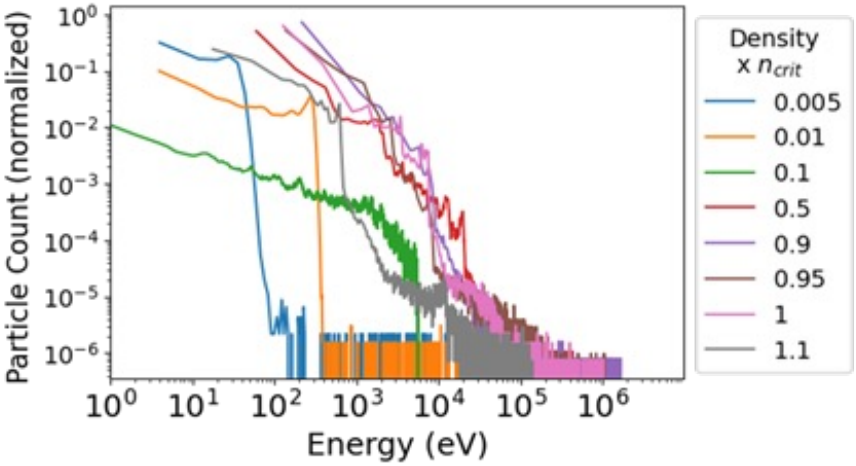
Particles reach >keV after 3 ps

(Barraza)

Energy gain and efficiency of High Density-LWFA

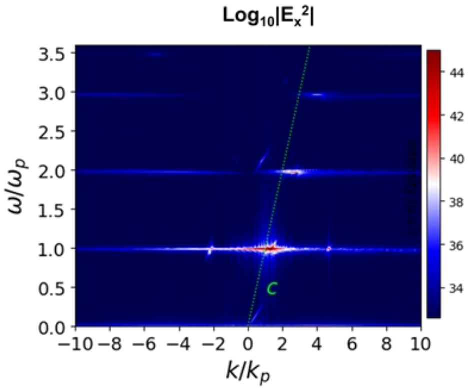
Dispersion relation of photons

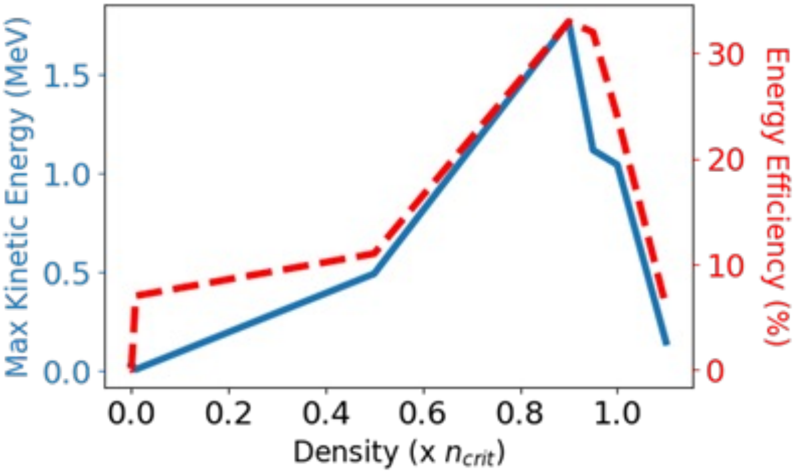




a_0 = 0.1

Dispersion relation for plasmons

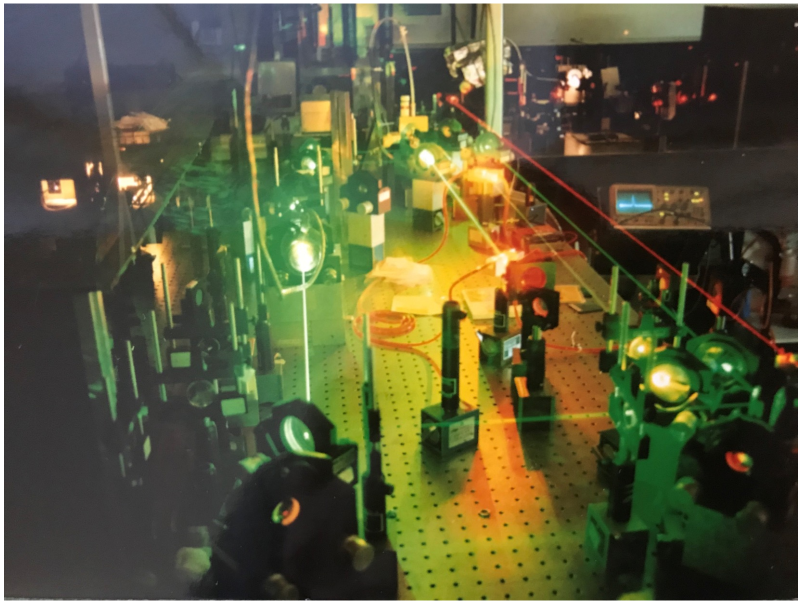




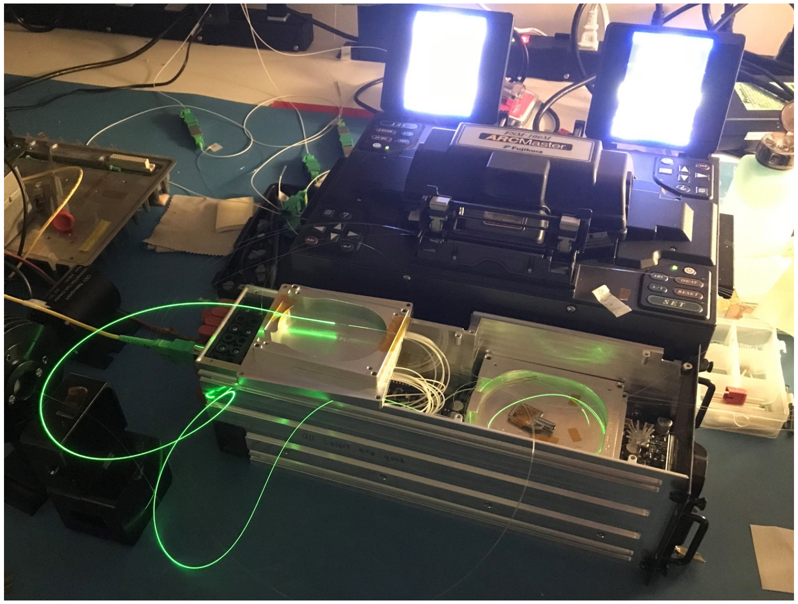
(Barraza)

Free-Space Laser vs. Fiber Laser

$a_0 \gtrsim 1$



$a_0 << 1$



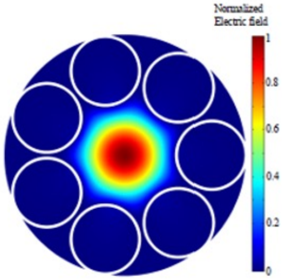
Fiber laser technology

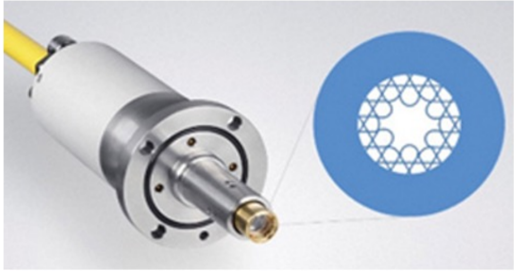
Application	**Average Power**	**Pulse Width**	**Peak Power**	**Spatial Mode**	**Focused Intensity**
Metal cutting (heat)	1 to 100 kW	Continous	same as average	MM	10^7 W/cm^2 (CW)
Semiconductor Processing	10 to 1000 W	1 to 100 ns	MW (10^6 W)	MM/SM	10^9 W/cm^2 (peak)
Glass cutting (cold ablation)	> 10 W	≤ 0.5 ps	Hundreds of MW	SM	10^{13} W/cm^2 (peak)
Portable LWFA (>10 keV eletrons)	1 to 10 W	≤ 1 ps	≥ GW (10^9 W)	SM	≥ 10^{14} W/cm^2 (peak)

MM: multi-mode (spatial) SM: single mode

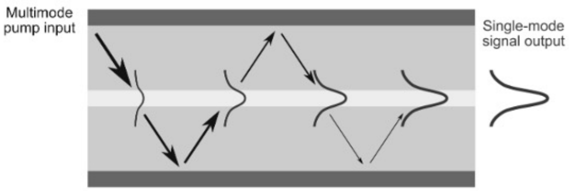
Under the collaboration with
Dr. Donna Strickland on going

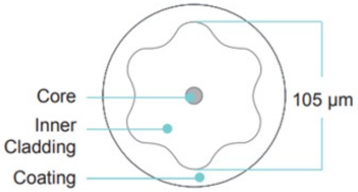
(Dr. W. J. Sha)

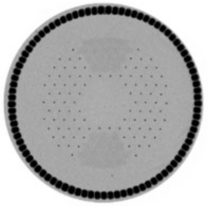




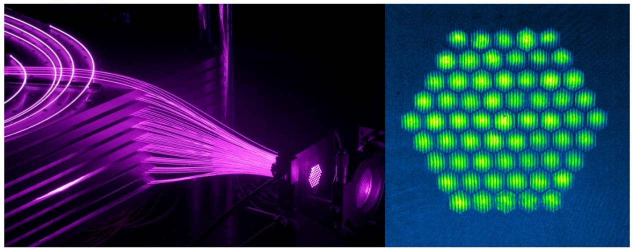
hollow fiber laser







CAN fiber lasers



Conventional electron accelerator (and X-ray) for Therapy

← 5-10m (next room) →

Electron energies by accelerator: 6-20MeV

→ X-rays

(Varian)

LWFA could provide high dose "FLASH" therapy

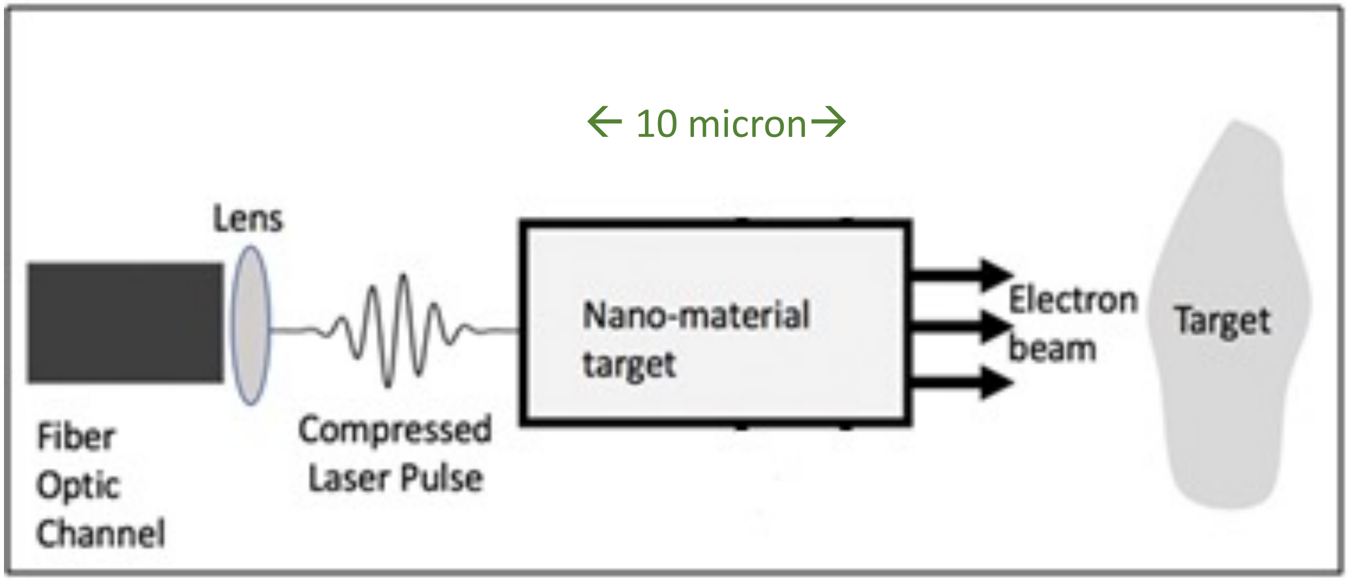
Furthermore, much tinier with **fiber**

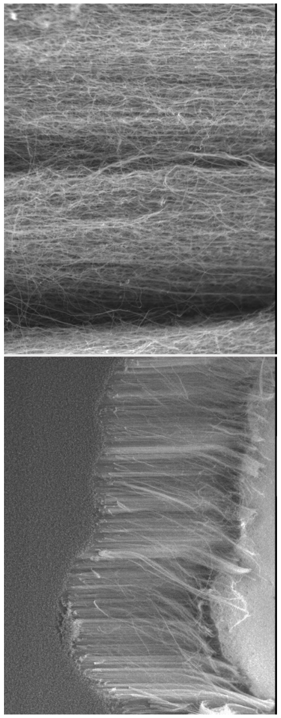
L_e ~ 1 cm / 10MeV → 10 micron / 10keV

^ ↑

Body penetration Cancer cell size

In situ / endoscopic fiber delivery of electron radiotherapy of cancer



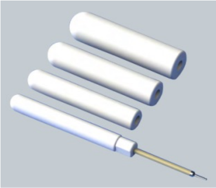


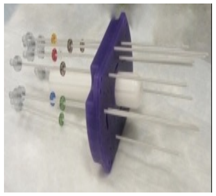
(Nano-lab)

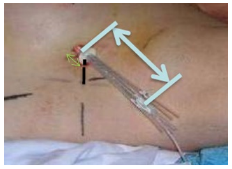
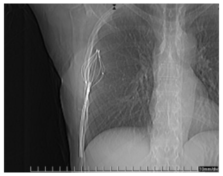
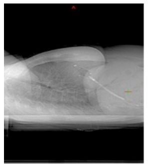
Fiber laser drives *in situ* **nanotube** target in front of **cancer cells**

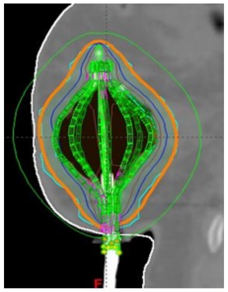
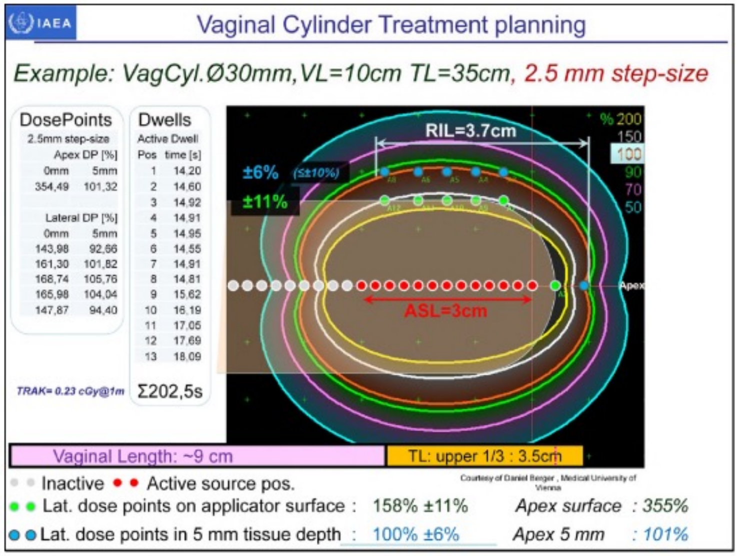
→ **Compactification**, **accurate** (no collateral damage), and **cheap**

Current treatment applications (from skin, vagina, uterine, breast, etc.)



IAEA Vaginal Cylinder Treatment planning

Example: VagCyl.Ø30mm,VL=10cm TL=35cm, 2.5 mm step-size

DosePoints
2.5mm step-size

Apex DP [%]	
0mm	5mm
354,49	101,32

Lateral DP [%]	
0mm	5mm
143,98	92,66
161,30	101,82
168,74	105,76
165,98	104,04
147,87	94,40

TRAK= 0.23 cGy@1m

Dwells

Pos	Active Dwell time [s]
1	14,20
2	14,60
3	14,92
4	14,91
5	14,95
6	14,55
7	14,91
8	14,81
9	15,62
10	16,19
11	17,05
12	17,69
13	18,09

Σ202,5s

Vaginal Length: ~9 cm | TL: upper 1/3 : 3.5cm

Courtesy of Daniel Berger, Medical University of Vienna

- ● ● Inactive ● ● Active source pos.
- ● ● Lat. dose points on applicator surface : 158% ±11% *Apex surface : 355%*
- ● ● Lat. dose points in 5 mm tissue depth : 100% ±6% *Apex 5 mm : 101%*

→ Much smaller, endoscopic in ours

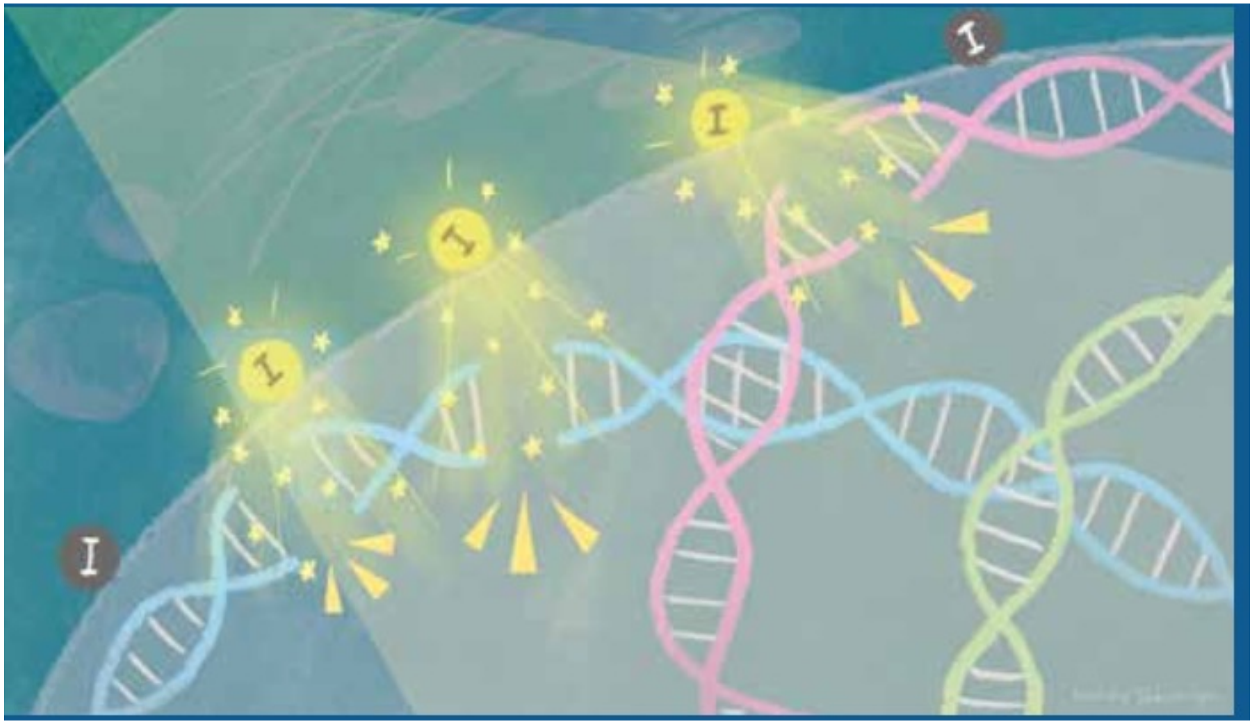
(D. Roa)

Vector nanomolecule with high-Z metal to target cancer cells for electron radiotherapy

High-Z: stop **electrons**

Nanomolecule **vector**:

attached to **cancer cell**

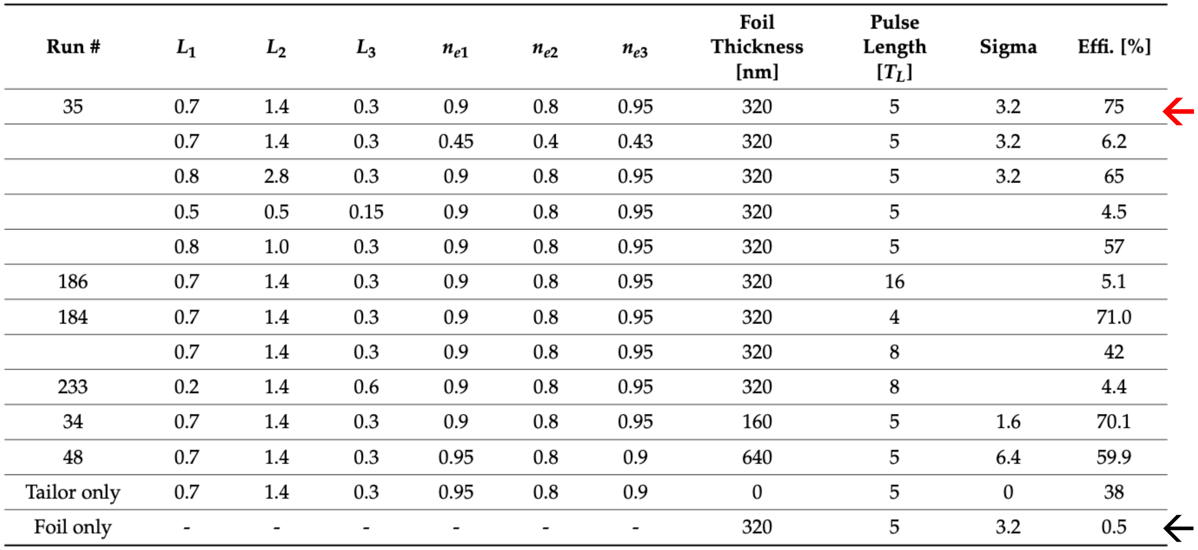


Nanomolecular vector medicine, (after F. Tamanoi, 2022)

Enhanced efficiency

Laser Ion Acceleration with the critical density trap

Table 1. Summary of the most successful runs based on laser-to-proton energy efficiency conversion. Parameter varied are in columns 2–8 are shown in Figure 1. The last two rows display the extreme cases of tailor region only and foil-only.



Run #	L_1	L_2	L_3	n_{e1}	n_{e2}	n_{e3}	Foil Thickness [nm]	Pulse Length [T_L]	Sigma	Effi. [%]
35	0.7	1.4	0.3	0.9	0.8	0.95	320	5	3.2	75
	0.7	1.4	0.3	0.45	0.4	0.43	320	5	3.2	6.2
	0.8	2.8	0.3	0.9	0.8	0.95	320	5	3.2	65
	0.5	0.5	0.15	0.9	0.8	0.95	320	5		4.5
	0.8	1.0	0.3	0.9	0.8	0.95	320	5		57
186	0.7	1.4	0.3	0.9	0.8	0.95	320	16		5.1
184	0.7	1.4	0.3	0.9	0.8	0.95	320	4		71.0
	0.7	1.4	0.3	0.9	0.8	0.95	320	8		42
233	0.2	1.4	0.6	0.9	0.8	0.95	320	8		4.4
34	0.7	1.4	0.3	0.9	0.8	0.95	160	5	1.6	70.1
48	0.7	1.4	0.3	0.95	0.8	0.9	640	5	6.4	59.9
Tailor only	0.7	1.4	0.3	0.95	0.8	0.9	0	5	0	38
Foil only	-	-	-	-	-	-	320	5	3.2	0.5

At near critical the group velocity of laser

$v_g \rightarrow 0$

Phase velocity plasma wave

$v_p \rightarrow 0$

“Shinkansen” stops to pick up heavy ions, whose trapping velocity

$v_{tr\ ion}$ = sqrt $(eE / M k)$ << $v_{tr\ e}$ = sqrt $(eE / m k)$

→ Efficiency: up by 2 orders of magnitude!

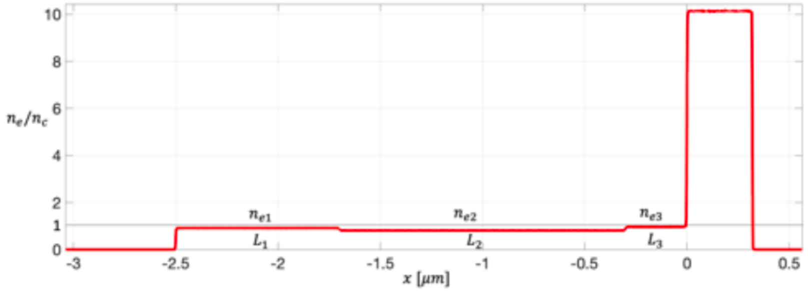
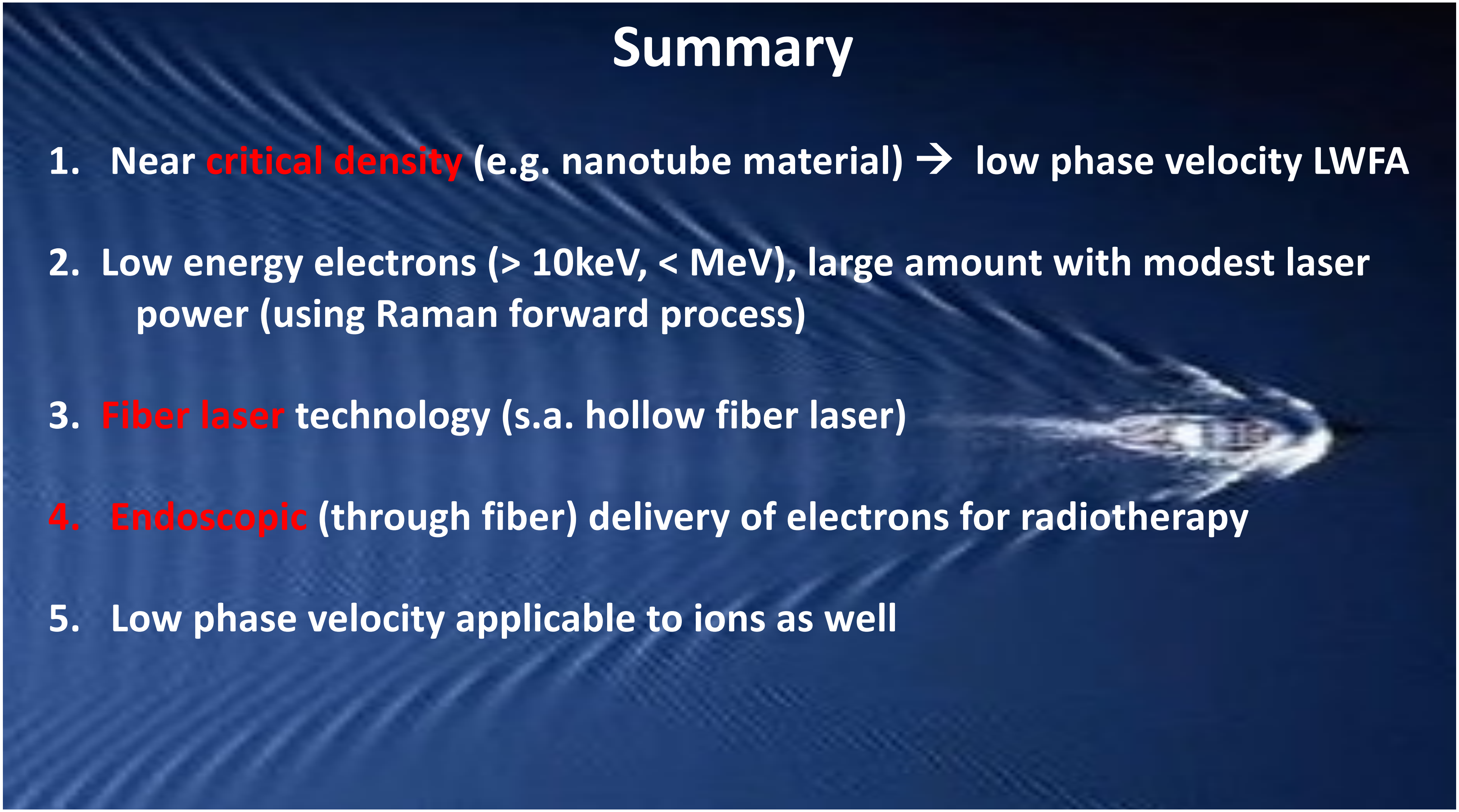


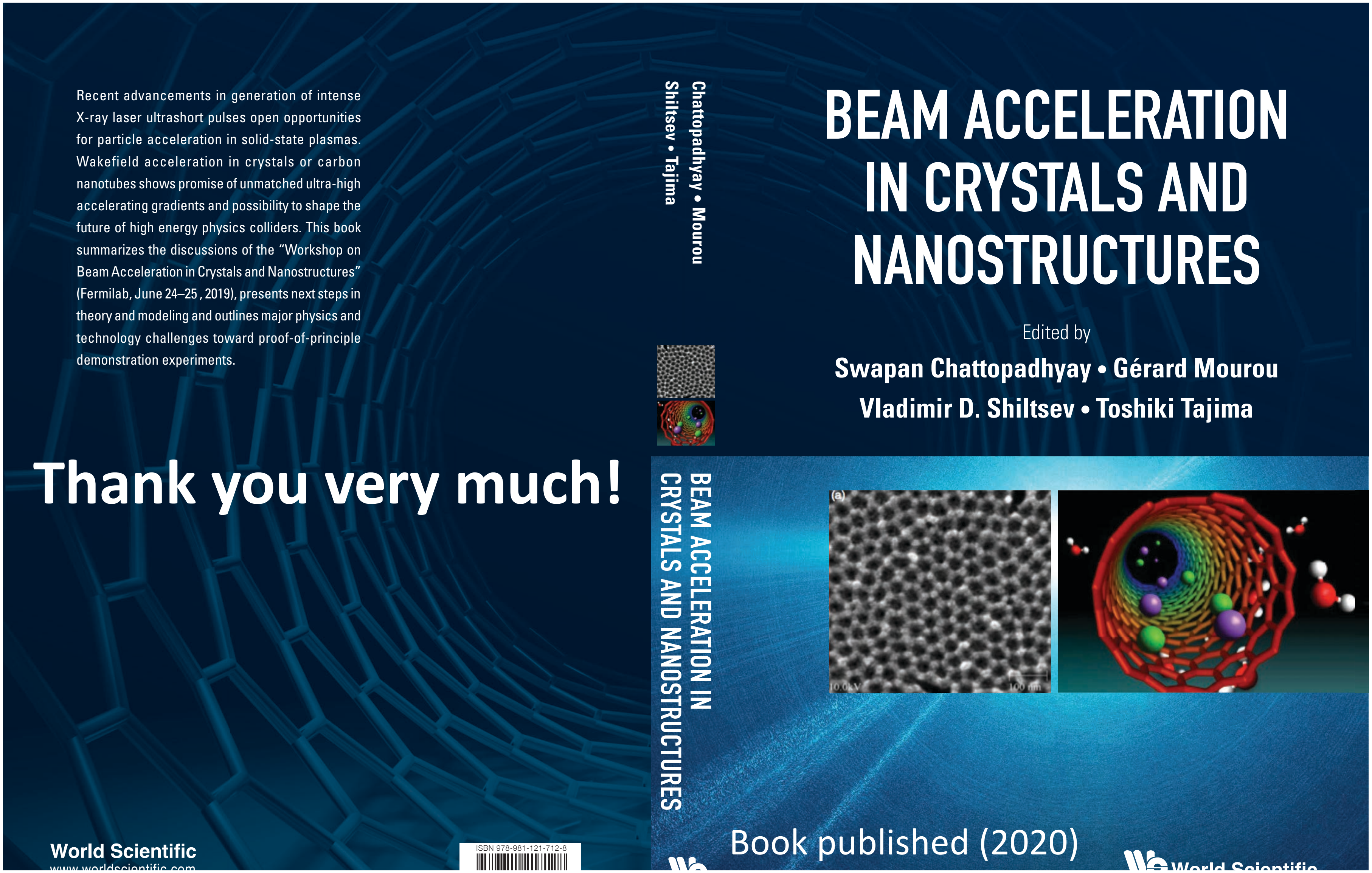
Figure 1. Density profile showing the shape of the tailor region and the foil. Inset shows the 6 free parameters to vary in addition to the foil density and thickness. The value of parameters shown is for the best-case scenario.

(Necas)



Summary

1. Near critical density (e.g. nanotube material) → low phase velocity LWFA
2. Low energy electrons (> 10keV, < MeV), large amount with modest laser power (using Raman forward process)
3. Fiber laser technology (s.a. hollow fiber laser)
4. Endoscopic (through fiber) delivery of electrons for radiotherapy
5. Low phase velocity applicable to ions as well



Recent advancements in generation of intense X-ray laser ultrashort pulses open opportunities for particle acceleration in solid-state plasmas. Wakefield acceleration in crystals or carbon nanotubes shows promise of unmatched ultra-high accelerating gradients and possibility to shape the future of high energy physics colliders. This book summarizes the discussions of the "Workshop on Beam Acceleration in Crystals and Nanostructures" (Fermilab, June 24–25, 2019), presents next steps in theory and modeling and outlines major physics and technology challenges toward proof-of-principle demonstration experiments.

World Scientific

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Chattopadhyay • Mourou
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BEAM ACCELERATION IN CRYSTALS AND NANOSTRUCTURES

BEAM ACCELERATION IN CRYSTALS AND NANOSTRUCTURES

Edited by

Swapan Chattopadhyay • Gérard Mourou
Vladimir D. Shiltsev • Toshiki Tajima

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Thank you very much!

Book published (2020)