Onsite Lab Symposium at UCSD (Feb.28, 2023)

Radiotherapy Application of High-Density Laser Wakefield Acceleration (LWFA)

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UCIRVINE

Acknowledgements:

D. Roa, W. J. Sha, D. Strickland, S. Nicks, E. Barraza, G. Mourou, F. Tamanoi, T. Ebisuzaki, H. Moyses, P. Taborek, V. Shiltsev, T. Kawachi

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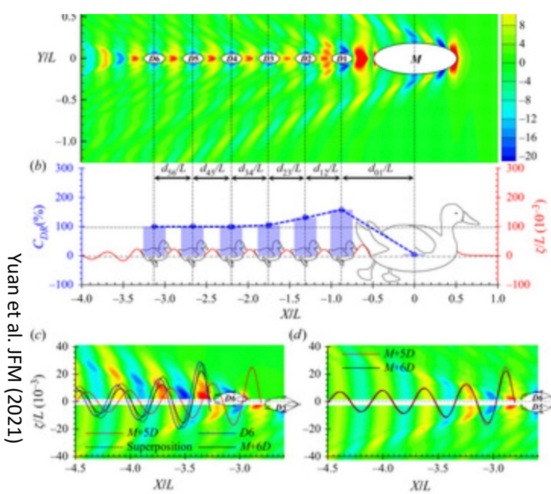
Toward laser wakefield accelerator (LWFA) at the tip of endoscope

1. Wakefields: in nature and laser-driven (LWFA, 1979)
2. High energy LWFA → nonrelativistic LWFA
3. Near critical density LWFA → beat wave approach
4. Fiber laser technology
5. Endoscopic fiber electron radiotherapy (2022)

Wake

Wake by a duck

Nature (or mother duck) shows us.

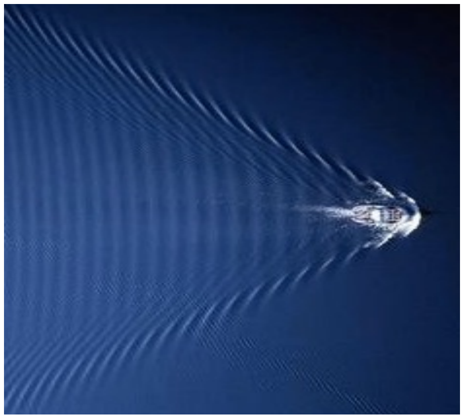


Yuan et al. JFM (2021)

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 #**

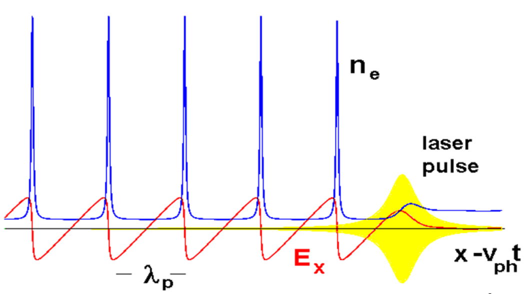


vs

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 ~ 10 >> 1 (relativistic wave)

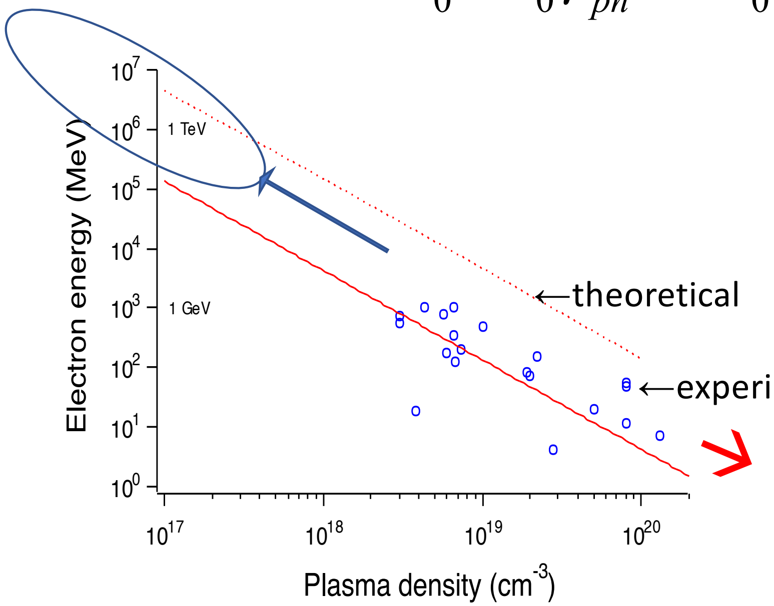
Tajima-Dawson field $E = m\omega_p c /e$ (~ GeV/cm)

With low phase velocity
More particle trapping

Theory of wakefield from extreme high energies to nanoscopic accelerator

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

(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) ←

n_e = 10^{16-19} (gas) ⟶ 10^{21} /cc(porous solid)

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

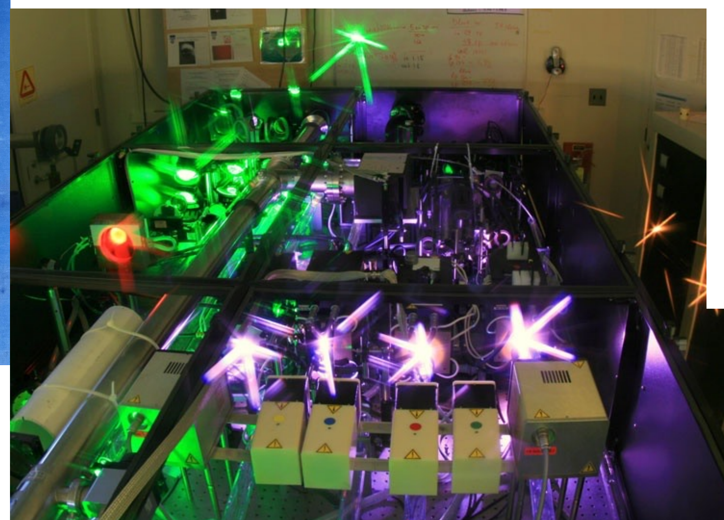
dephasing length

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

pump depletion length

Demonstration (1994), realization, and applications of laser wakefield accelerators (1979)

(2004)



(Michigan)

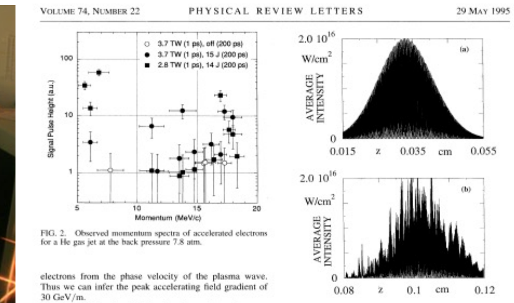

VOLUME 74, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 1995

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.

First expt: Nakajima, et al (1994, 1995)

Theory: Tajima-Dawson (1979)

4 GeV laser accelerator LBL

←

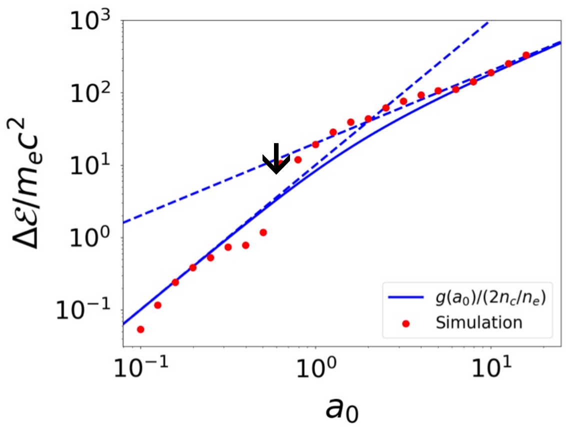
3GeV Synchrotron SOLEIL

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

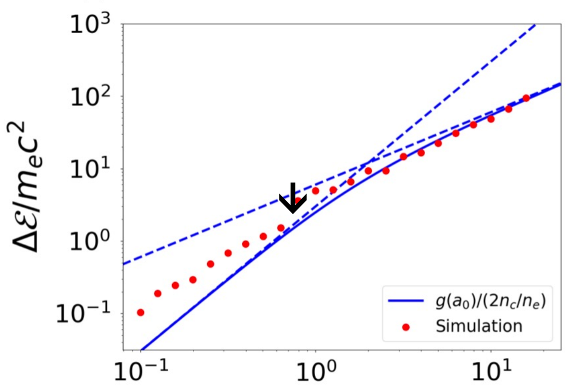
v_g (group velocity of photon) = v_p (phase velocity of plasma wave) << c

(S. Nicks, 2019)

Energy gain

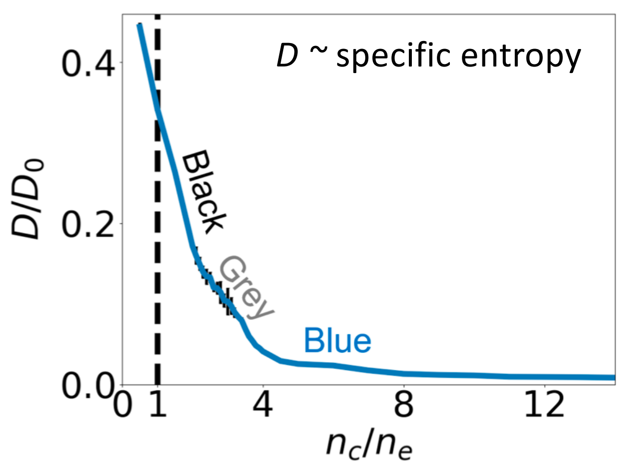


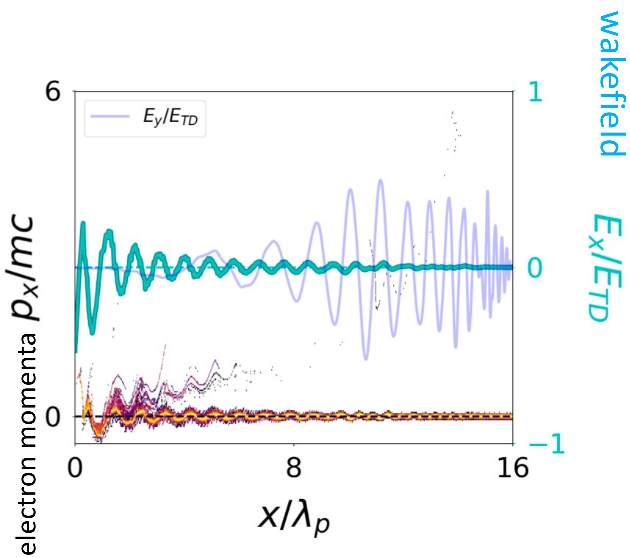
(a) E_{max} vs a_0 for fixed density ratio of 10



$n_{cr} / n_e = 3$

$n_e \sim n_{cr}$



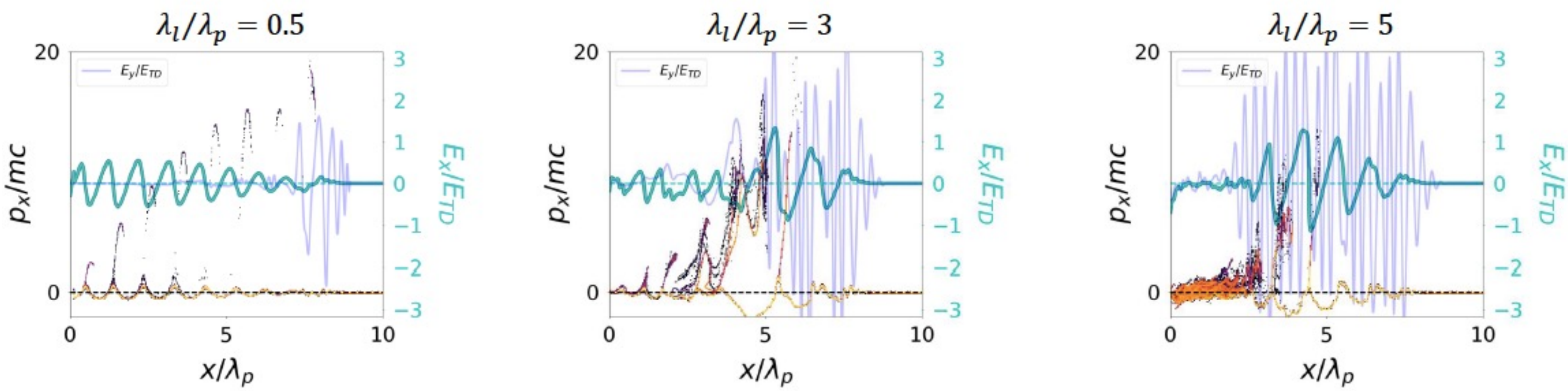


LWFA in low energy high-density regime

S. Nicks et al. Int. J. Mod. Phys. A**34**, 1934019 (2019).

Self-Modulation

- Fiber lasers → long pulse better
- Self-modulation: long pulse breaks → small pulses
- Pulse length λ_l/λ_p scanned, $n_c/n_e = 10$, $a_0 = 1$
- Long pulses → Laser/wakefield modulated



Simulation study: low intensity laser near critical density

Barraza, Tajima, Strickland, Roa (Photonics, 2022)

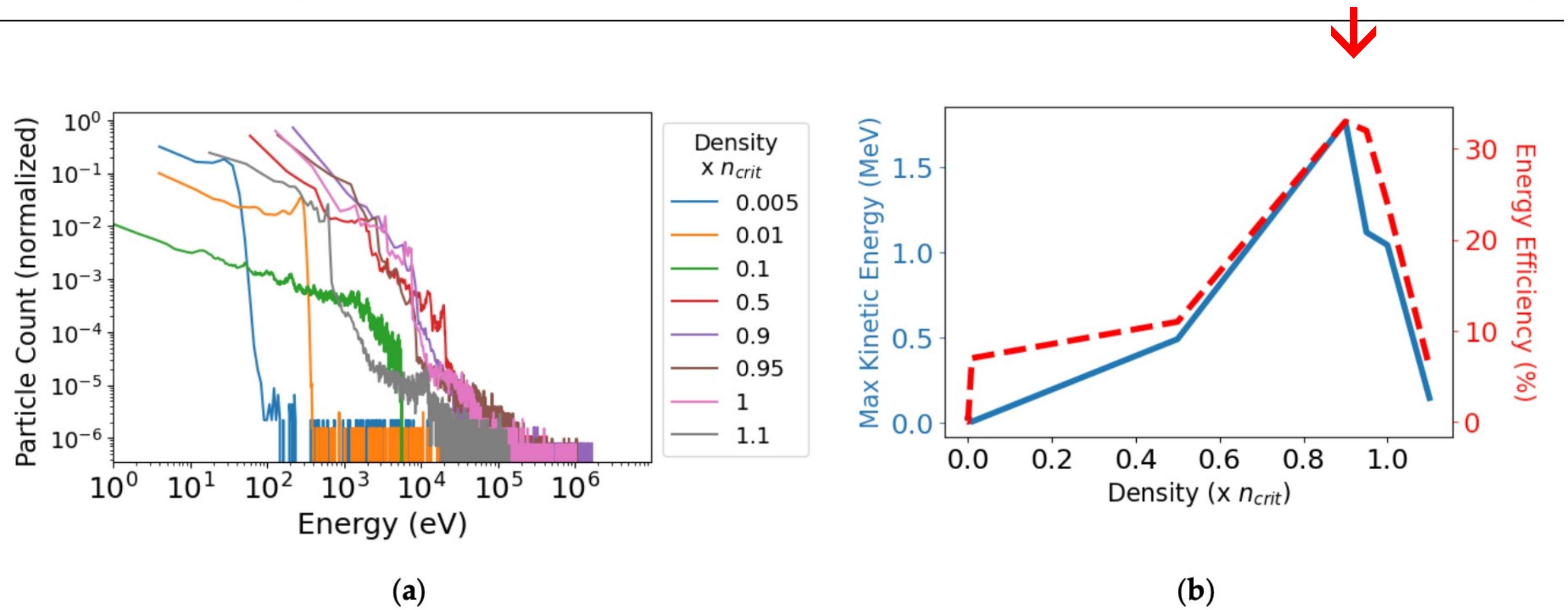
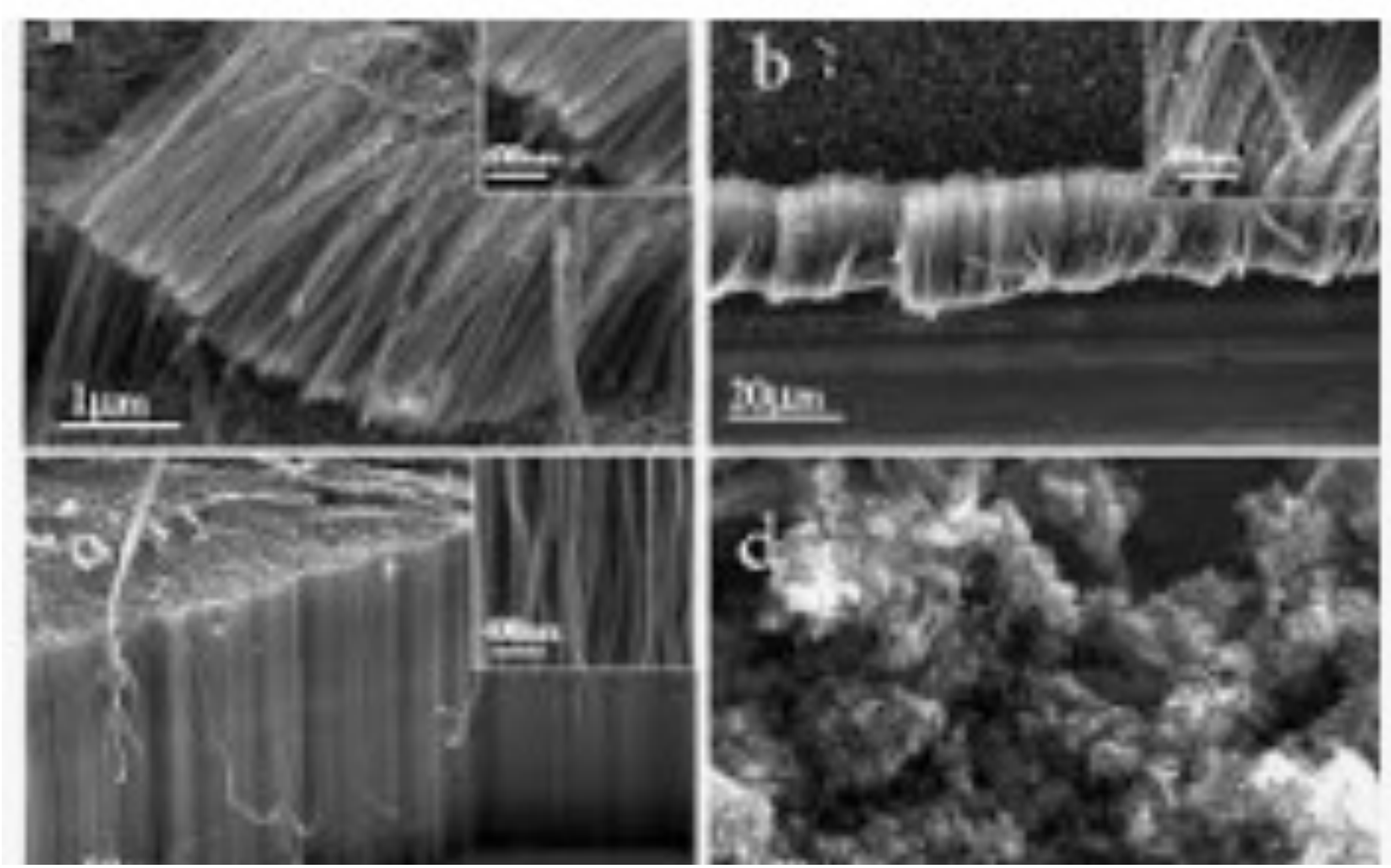


Figure 3. Energy distributions, maximum kinetic energies, and laser to total particle energy efficiency with respect to plasma density for BWA simulations after 1 ps using gaussian lasers with intensities of a, a = 0.1, and pulsewidth of 100 fs. The seed laser wavelength was held at λ =1 μm

Carbon nanotubes on a substrate:

→ toward **Carbon Nanoforest** (instead of plasma w/vacuum)



Laser Wakefield Acceleration near critical density

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

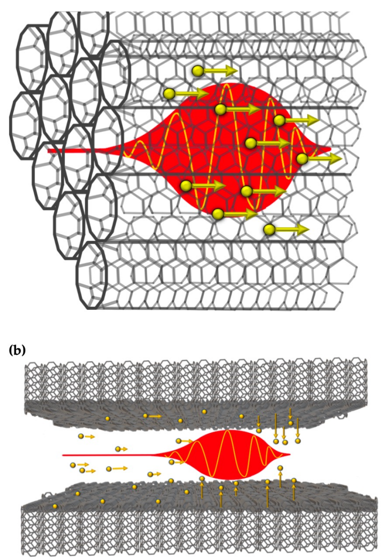
gaseous plasma → solid nanotube

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

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

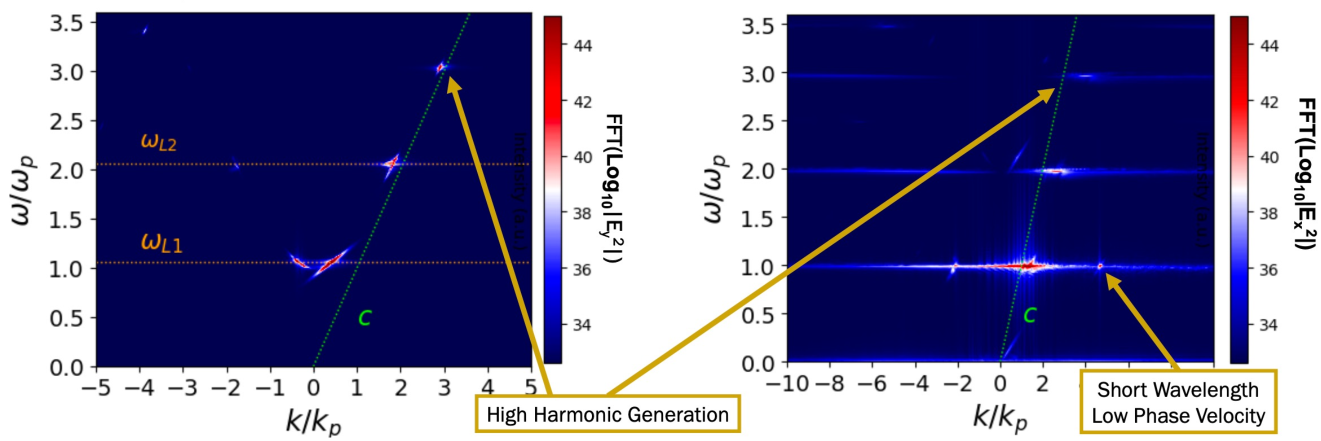
← overlap of plasma waves with different v_p

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

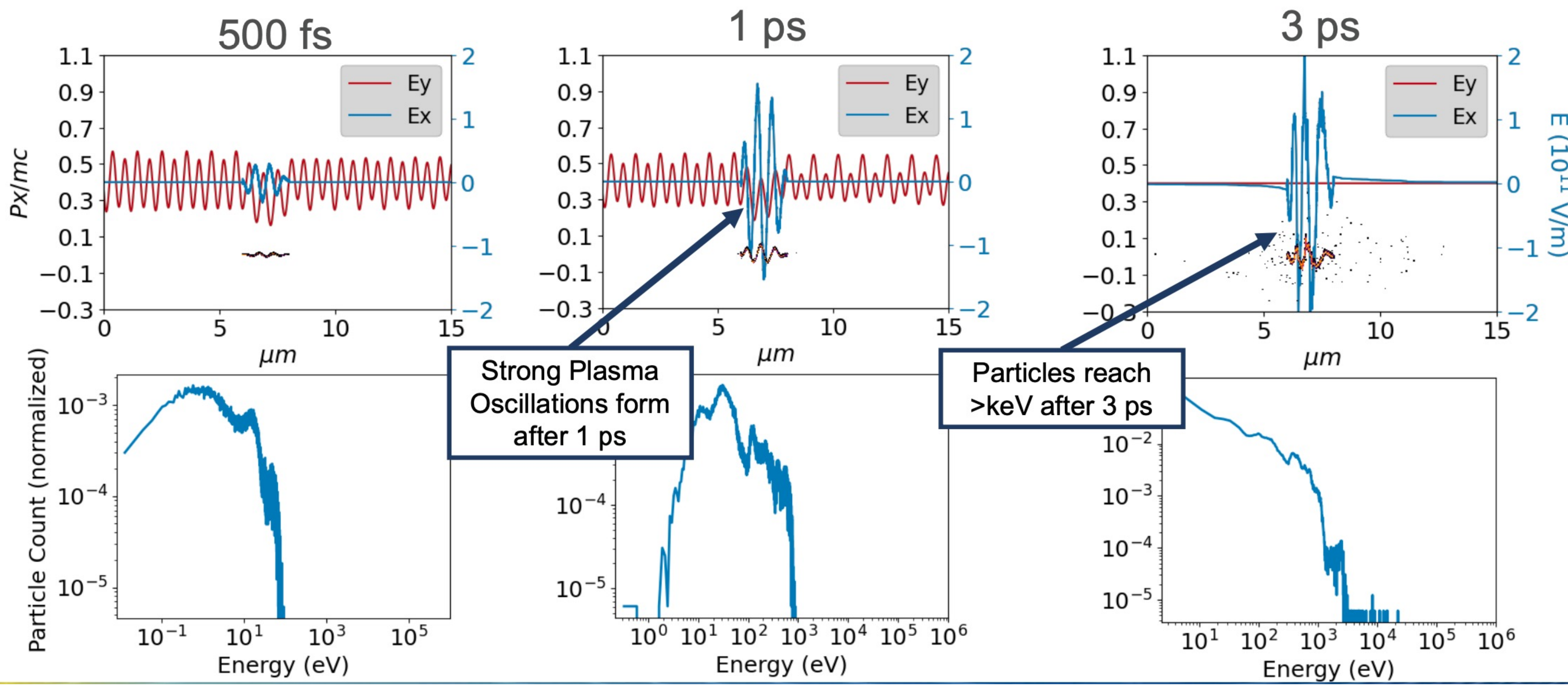


Dispersion Relation: FFT(Log_{10}E)

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

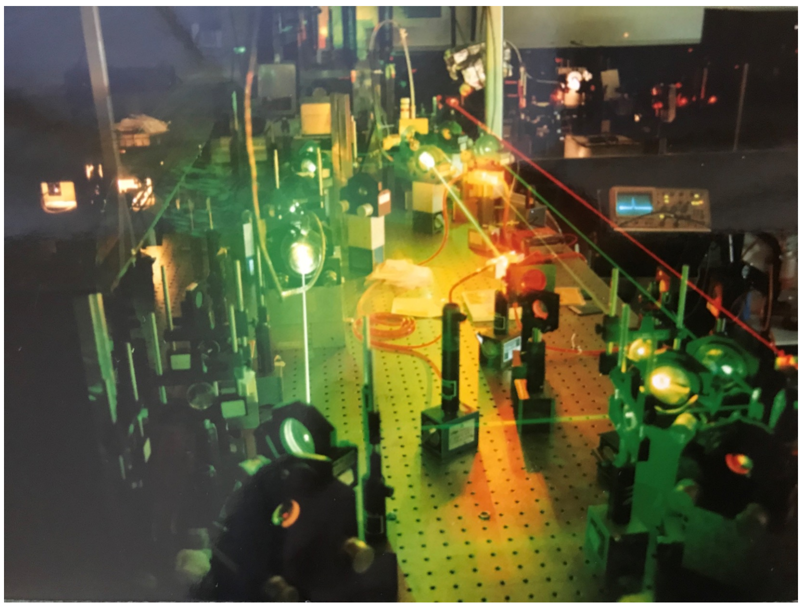


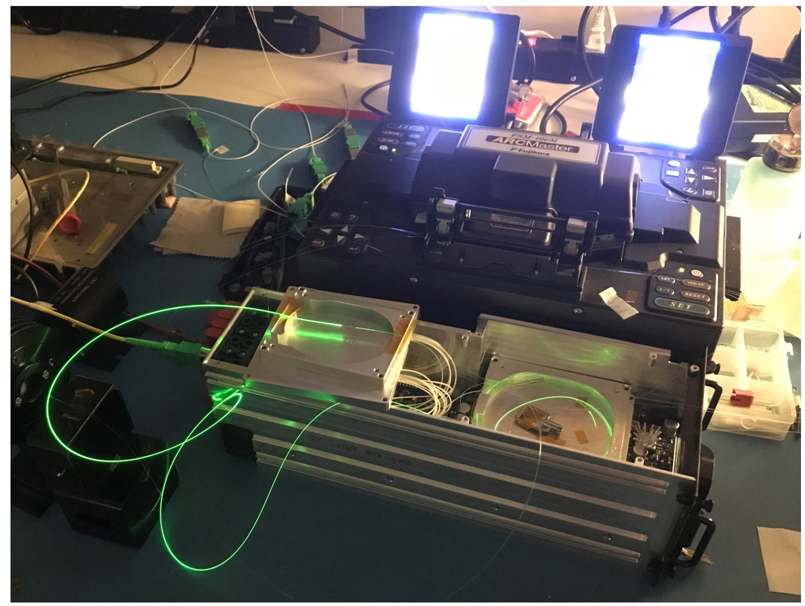
Target Foil Simulations in time: $a_0 = 0.007 \rightarrow 10^{14} W/cm^2$ with 2 μm Target



(Barraza)

Free-Space Laser vs. Fiber Laser





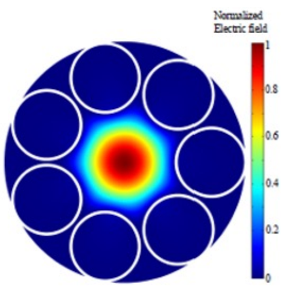
Fiber laser technology

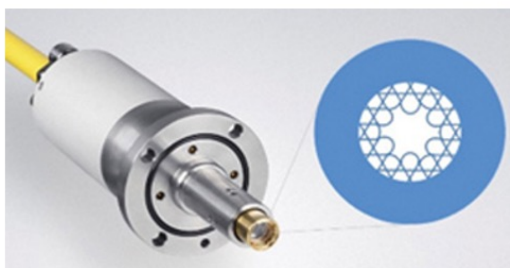
Application	Average Power	Pulse Width	Peak Power	Spatial Mode	Focused Intensity
Metal cutting (heat)	1 to 100 kW	Continous	same as average	MM	10^7 W/cm^2 (CW)
Semiconductor Processing	10 to 1000 W	1 to 100 ns	MW (10^6 W)	MM/SM	10^9 W/cm^2 (peak)
Glass cutting (cold ablation)	> 10 W	≤ 0.5 ps	Hundreds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

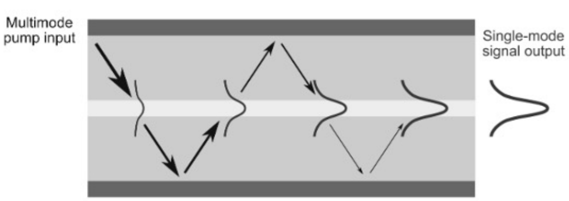
(Dr. W. J. Sha)

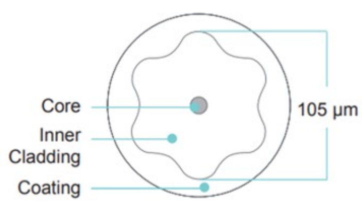


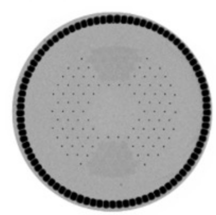


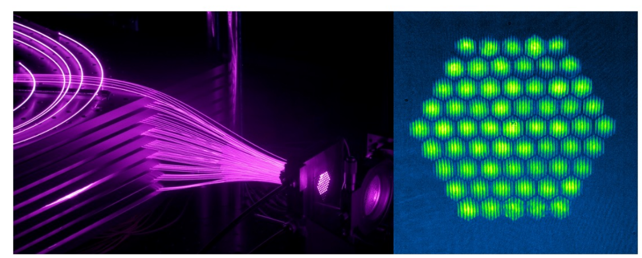
hollow fiber laser

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

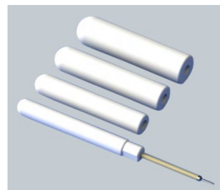
Furthermore, much tinier with **fiber**

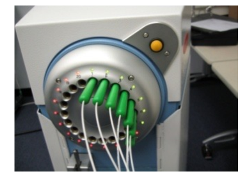
L_e ~ 1 cm / 10MeV → 10 micron / 10keV

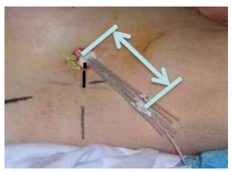
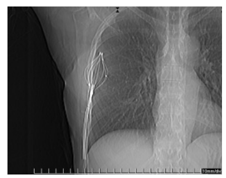
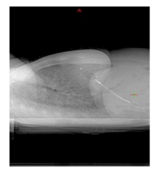
^ Body penetration

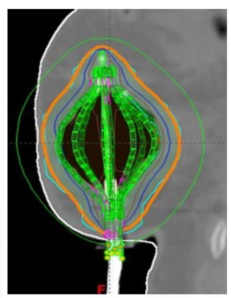
↑ Cancer cell size

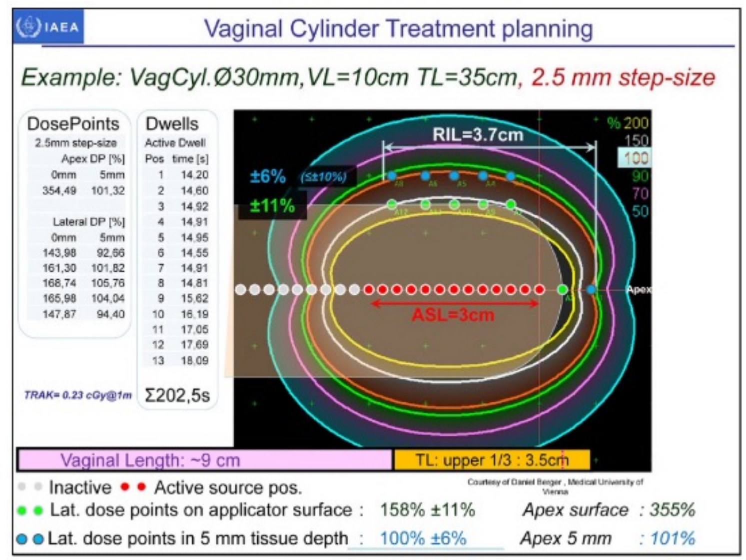
Current radiotherapy applications (from skin, vagina, uterine, breast, etc.)

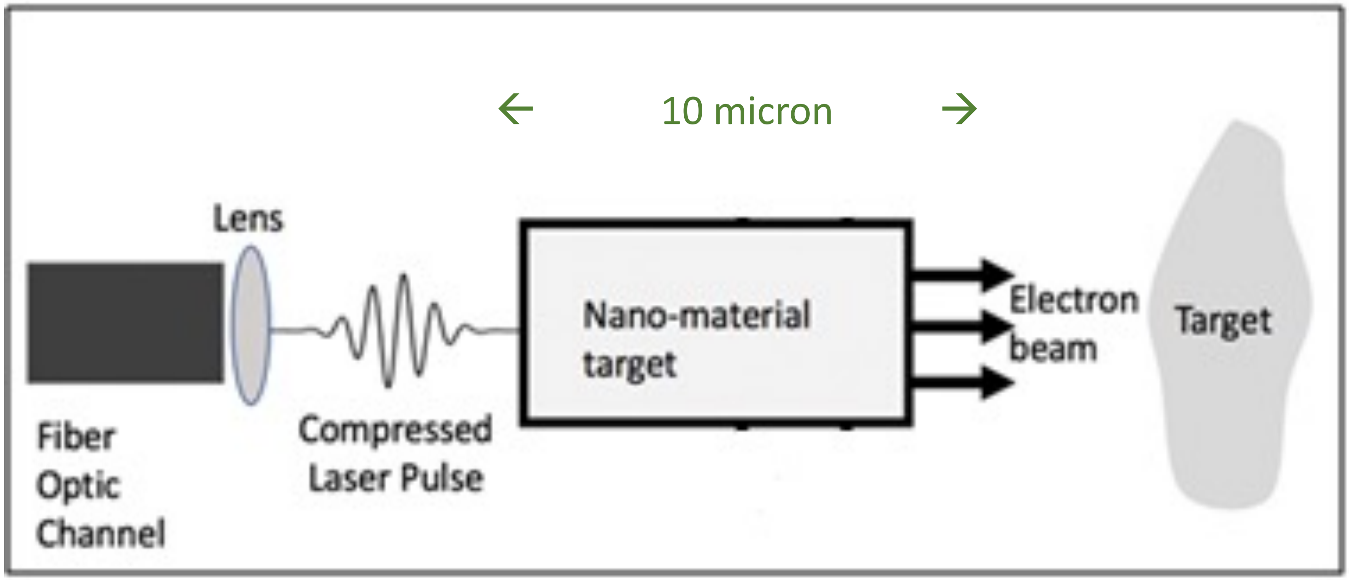





→ Much smaller, endoscopic in ours

(Prof. D. Roa)

In situ / endoscopic fiber delivery of electron radiotherapy of cancer (Roa et al, 2022)



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

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

Cost **estimate** comparison with Brachy therapies

↓

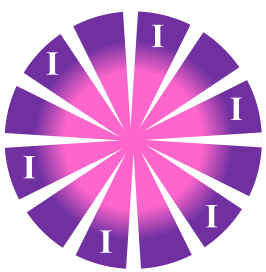
	LWFA – HDR	Iridium-192–HDR	Cobalt-60–HDR
Purchase Estimate	$100K - $300K	$700K - $900K	$700K - $900K
Room Shielding	None	$200K - $500K	$200K - $500K
Source Replacement	None	~$10K every 4-6 months	~130K every 60 months
Downtime due to Source Replacement	None	1-2 days	1-2 days

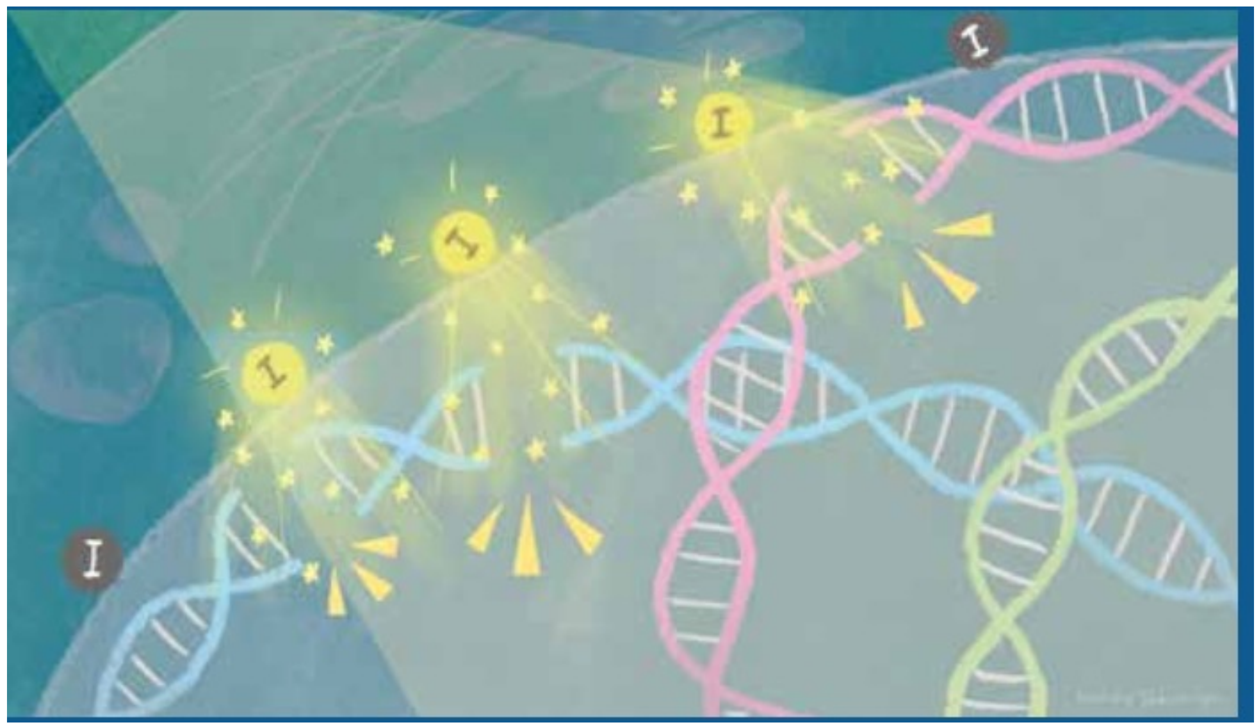
(Prof. D. Roa, preliminary estimate)

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

High-Z attached to the vector:
- stop **electrons**

Nanoparticle **vector**:
- delivered to **cancer cell**





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

Summary

1. Near critical density (e.g. nanotube material) → low phase velocity LWFA

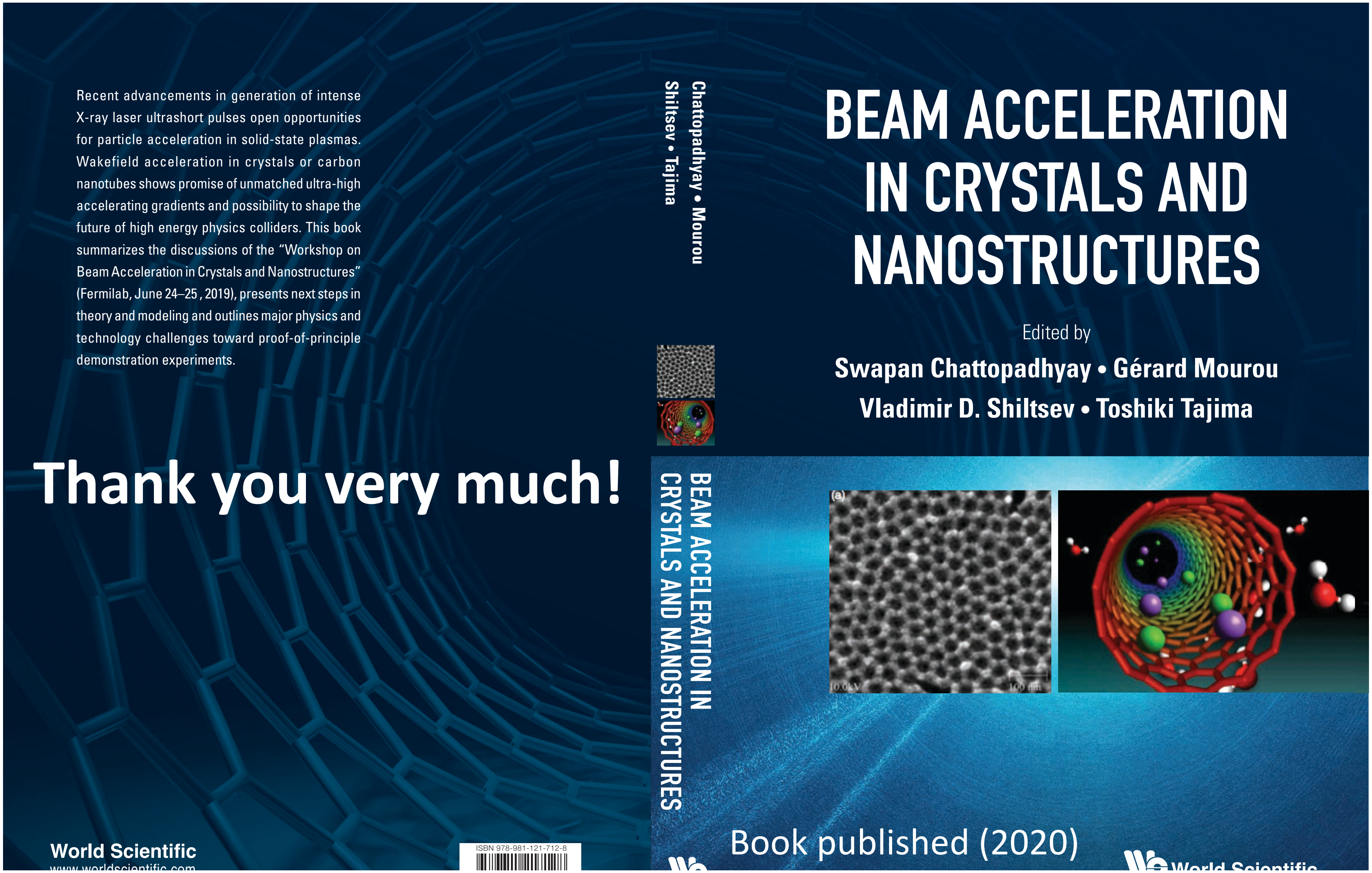
2. Low energy electrons (> 10keV, < MeV), large amount with fiber laser power (using Raman forward process)

3. Fiber laser technology (s.a. hollow fiber laser)

4. Endoscopic (through fiber) delivery of electrons for radiotherapy
   ← replacing Brachy therapy

5. Nanomolecule vector (with high-Z particle attached) →
   further accuracy, focus of electrons on cancer cells

Thank you very much!



Book published (2020)