LSSE, OPIC (April 18, 2022)

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

T. Tajima[a] and D. Roa[b]

[a] Department of Physics and Astronomy, [b] Department of Radiation oncology
University of California at Irvine , CA, 92697 USA

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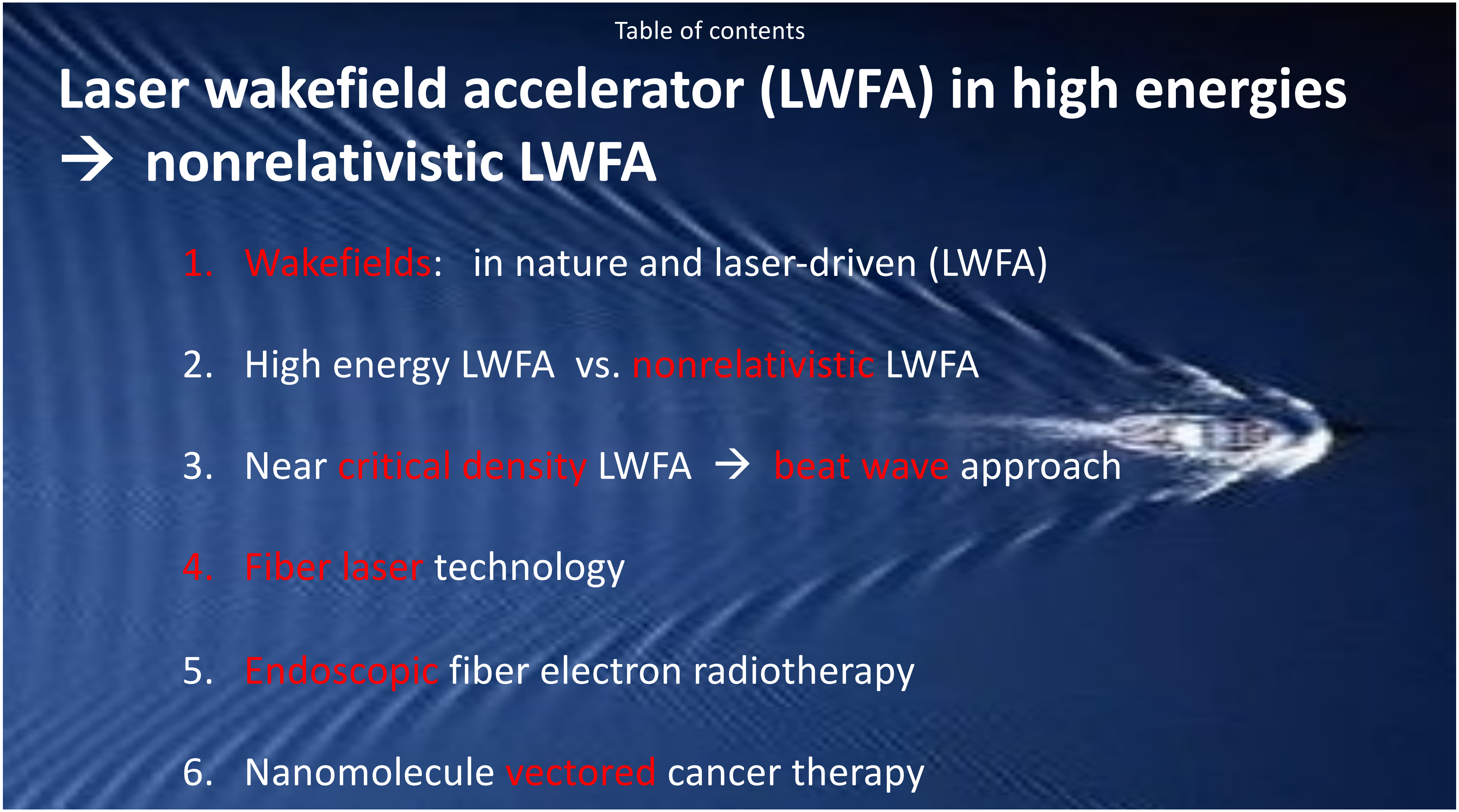

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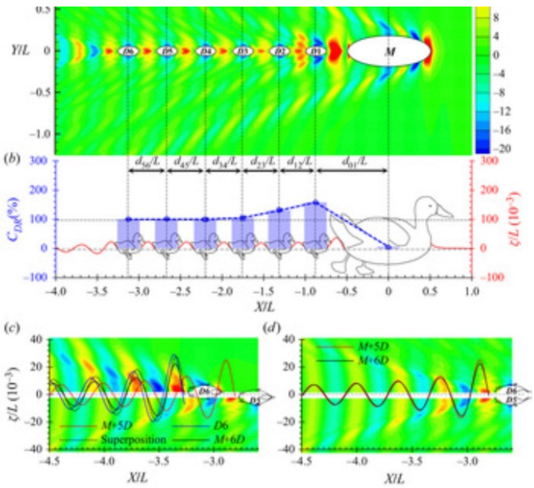
Wake acceleration

Bow wake and stern wake
Nature (or mother duck) shows us.

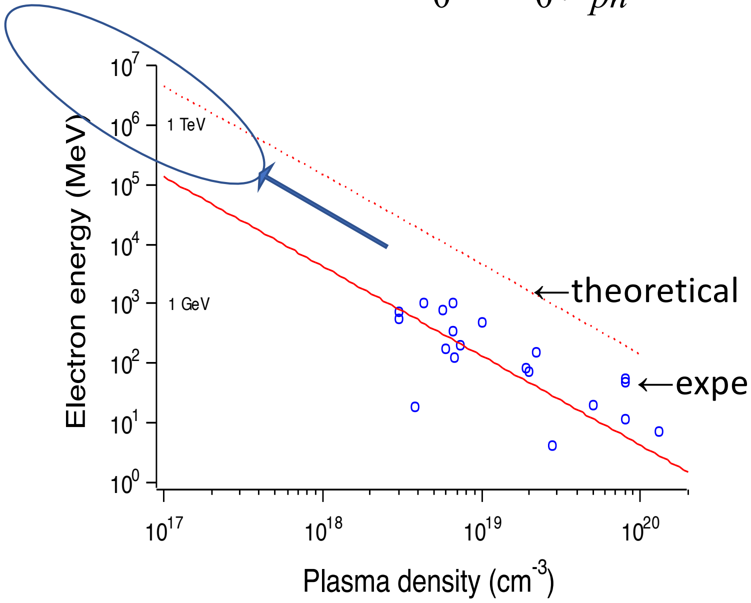


Yuan et al. JFM (2021)

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

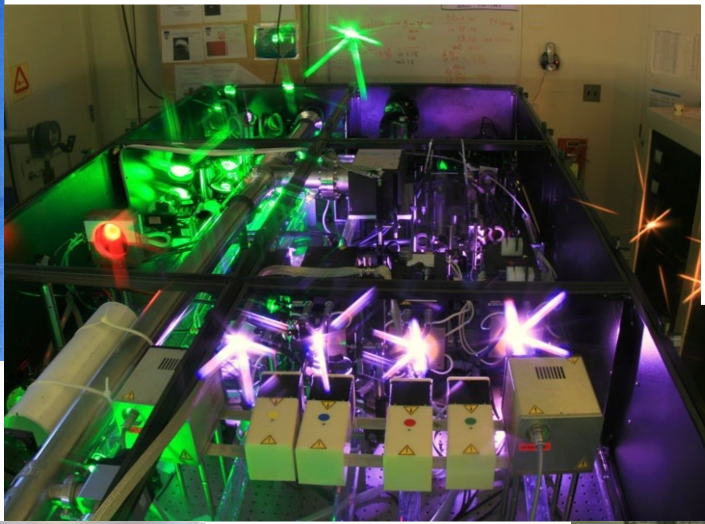
Offshore tuna ranches
A threat to US waters?

Protein folding
Escape from the ribosome

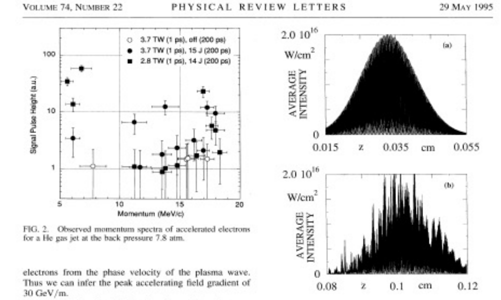
The Earth's hum
Sounds of air and sea

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)

4 GeV laser accelerator LBL

←

3GeV Synchrotron SOLEIL

Relativistic vs Nonrelativistic LWFA

1. **High phase velocity paradigm**: Tajima-Dawson (1979) $v_{ph} \rightarrow$ large (close to c)

2. **Relativistic amplitude of LWFA** : $a_0 > 1$

3. **Relativistic coherence** (Tajima, 2010)

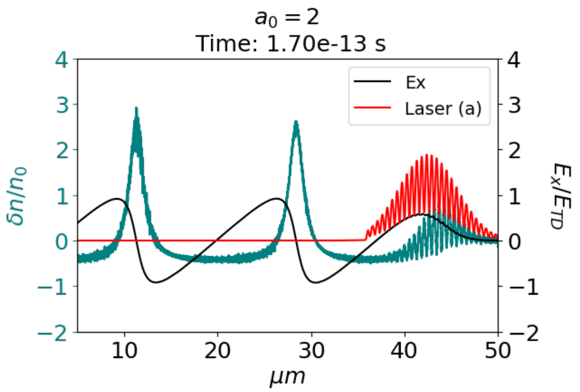
Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega_p v_{ph}/e$

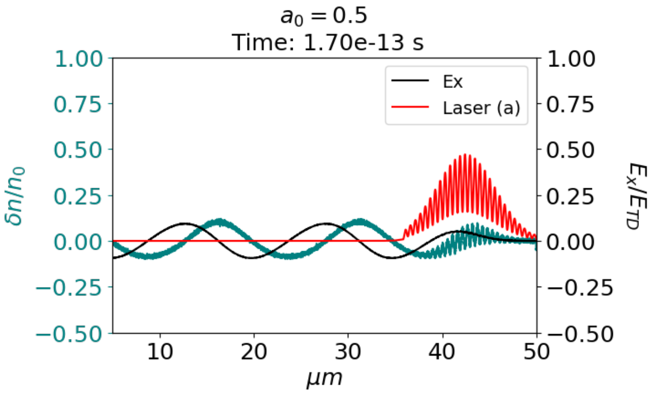
Relativistic coherence enhances beyond the Tajima-Dawson field: $E = m\omega_p c\, a_0/e$ (~ GeV/cm)

No wave breaks and wake **peaks** at relativistuic regime v≈c

Wave **breaks** at v<c at non-relativistic regime

Relativistic coherence (Tajima, 2010) vs **Nonrelativistic cases** (today: more to follow)



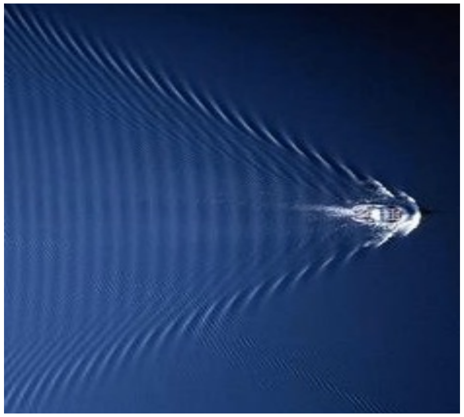


$a_0 > 1$ vs $a_0 < 1$

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 #**

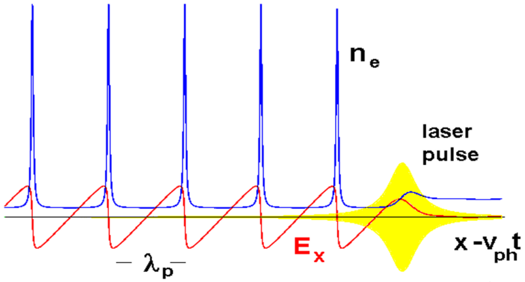


vs

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*)

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

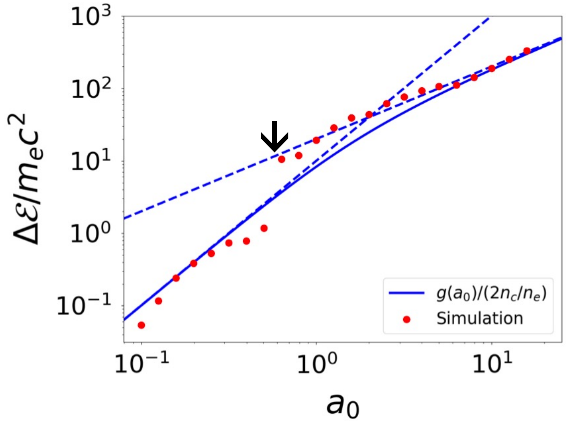
Tajima-Dawson field $E = m\omega_p c/e$ (~ GeV/cm)

With low phase velocity

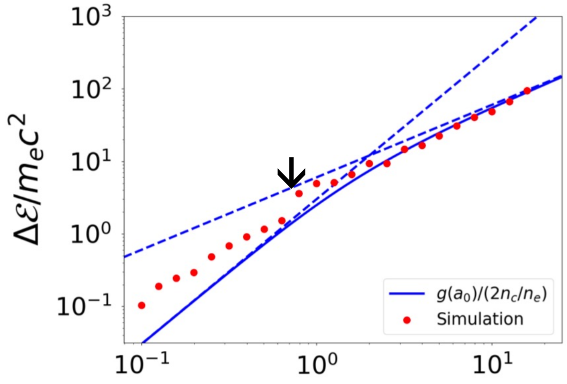
More particle trapping

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

Energy gain

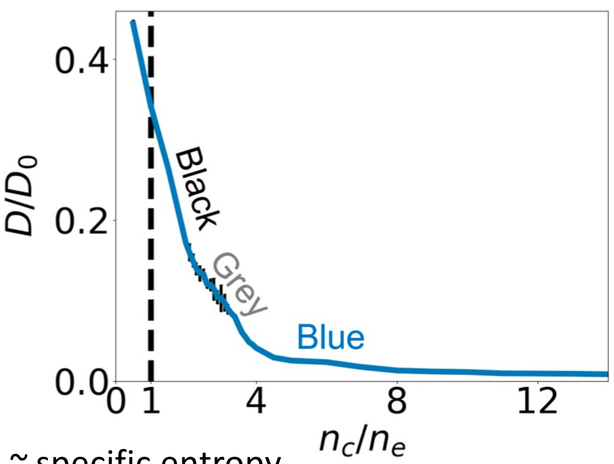


(a) E_{max} vs a_0 for fixed density ratio of 10



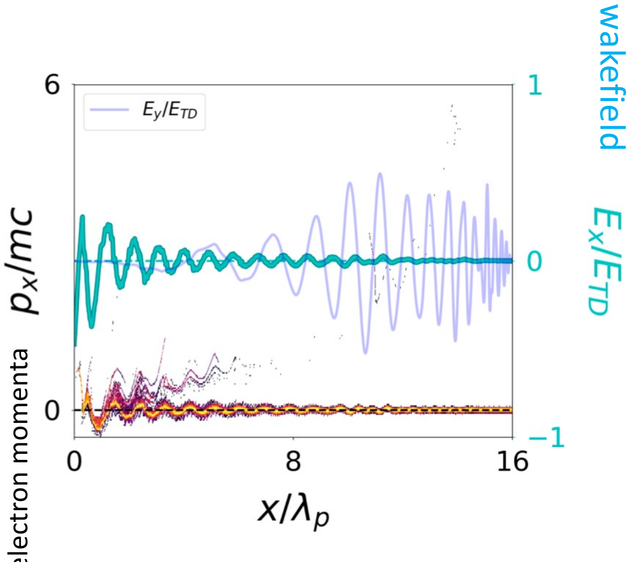
v_g (group velocity of photon) = v_p (phase velocity of plasma wave) << c

$n_e \sim n_{cr}$



D ~ specific entropy

(S. Nicks)



Laser Wakefield Acceleration near critical density

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

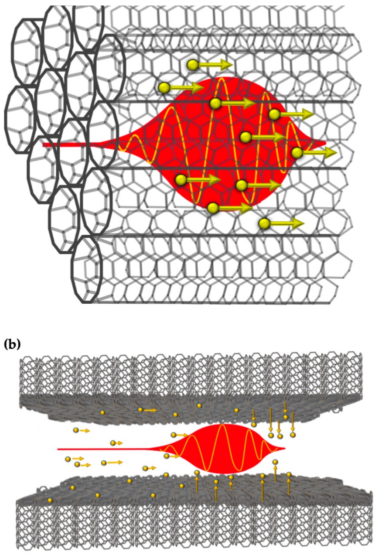
gaseous plasma → solid nanotube

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

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

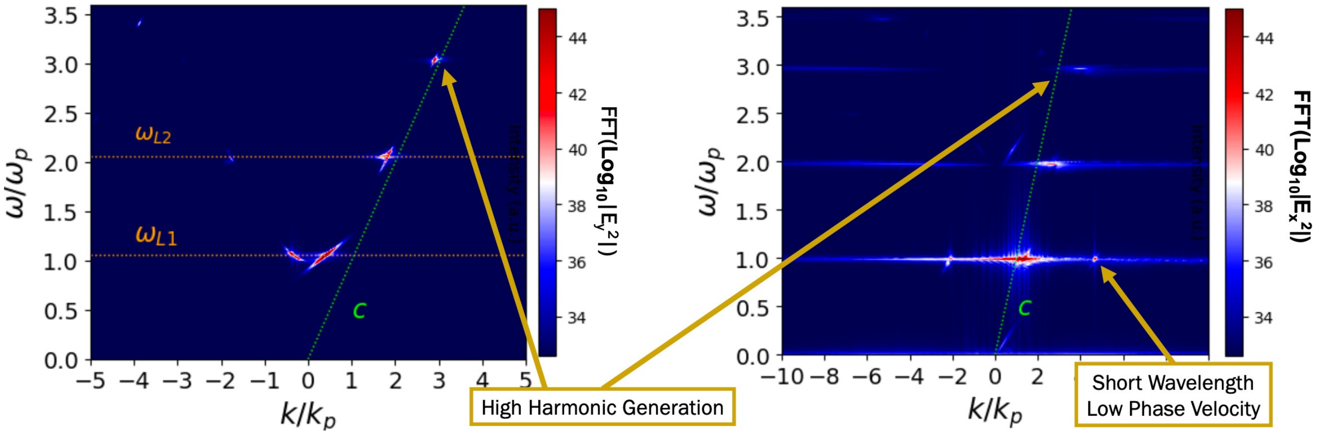
←overlap of plasma waves with different v_p

← 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

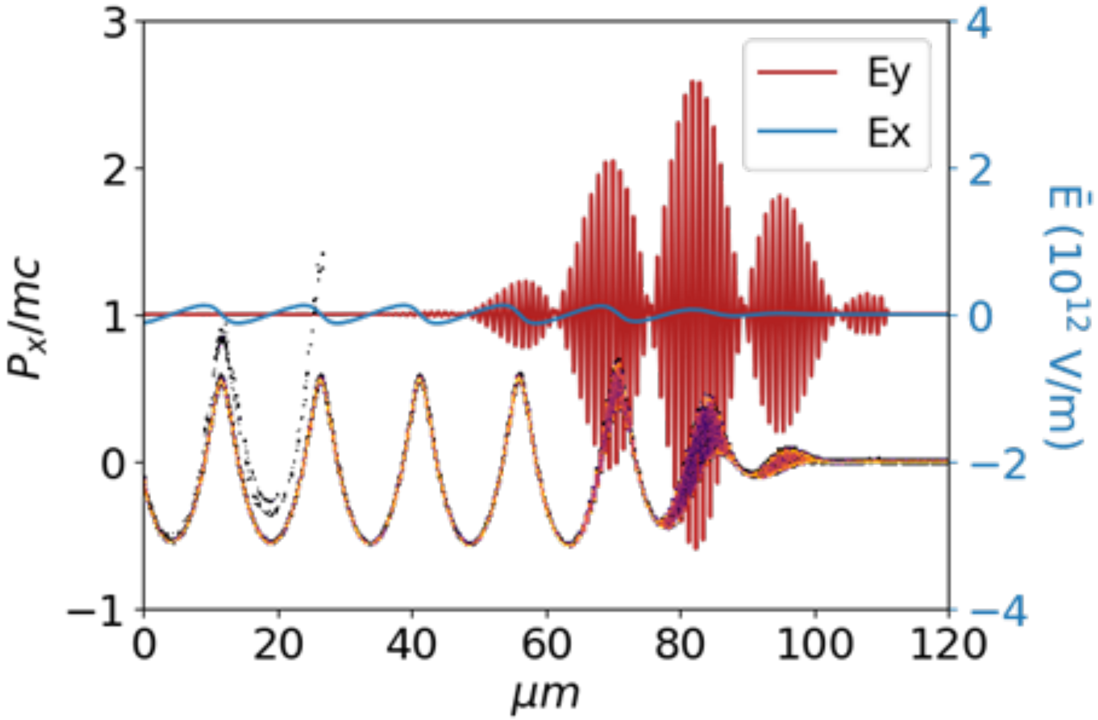


High Harmonic Generation

Short Wavelength
Low Phase Velocity

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



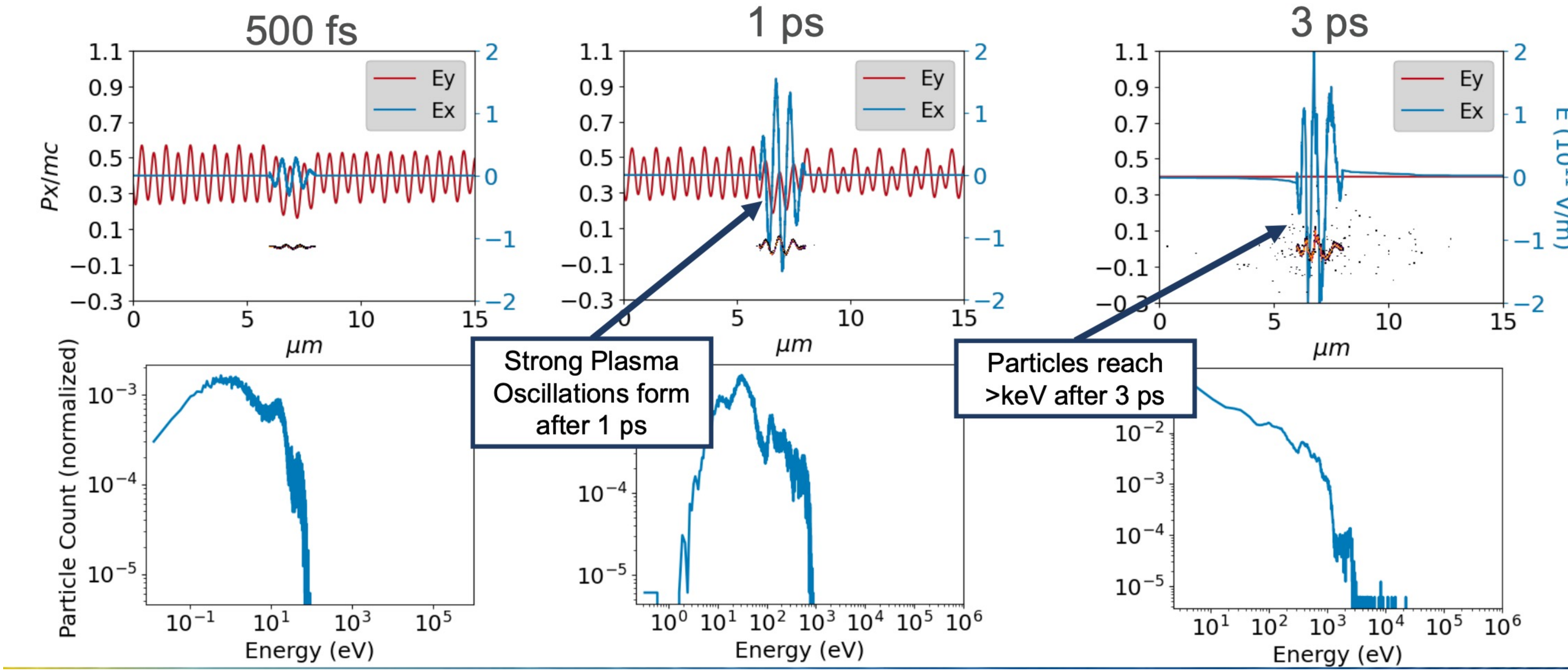
$$v_{ph} = \frac{\omega_p}{k_p} = \frac{\omega_0 - \omega_1}{k_0 - k_1}$$

$$v_g = \frac{\partial \omega}{\partial k} = \frac{c}{\text{[illegible]}}\sqrt{1 - n_e/n_c}$$

Nonrelativistic limit of energy gain

$$W_{max,nr} = \frac{\pi}{2} m v_{ph}^2 a_0^2 \left(\frac{\omega_0}{\omega_p}\right).$$

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



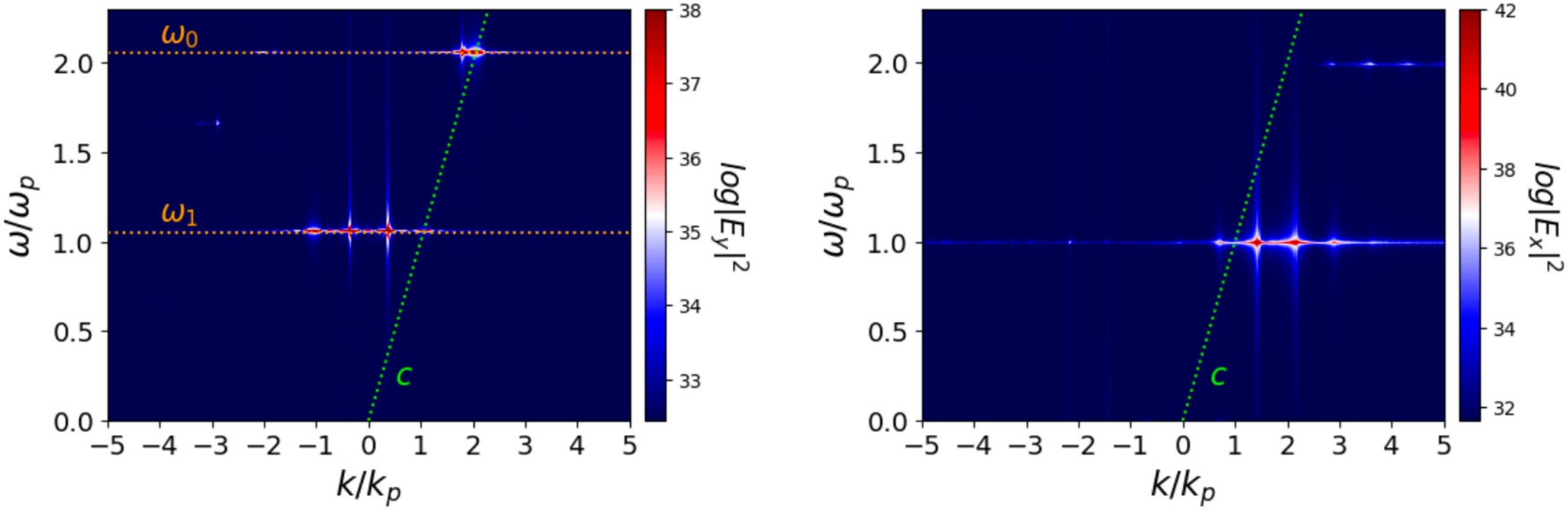
Strong Plasma Oscillations form after 1 ps

Particles reach >keV after 3 ps

(Barraza)

Beat wave excitation of plasma wave

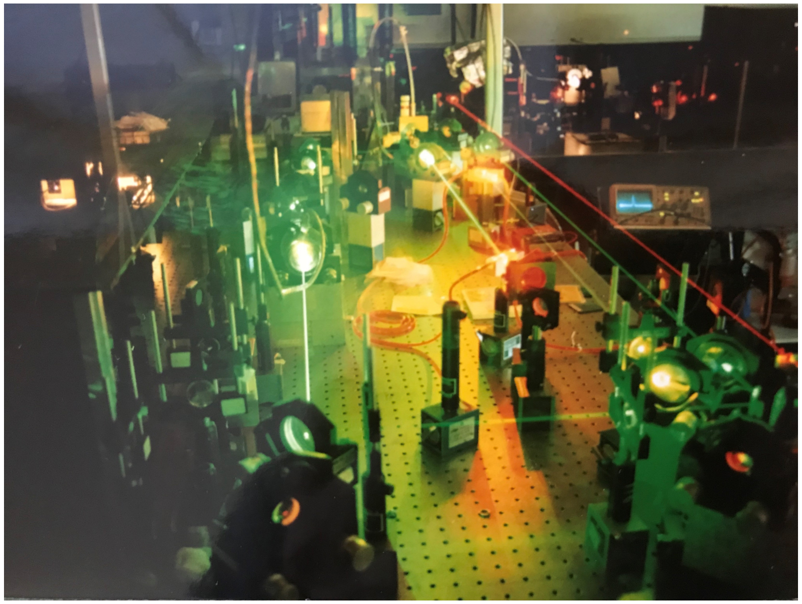
Raman forward scattering

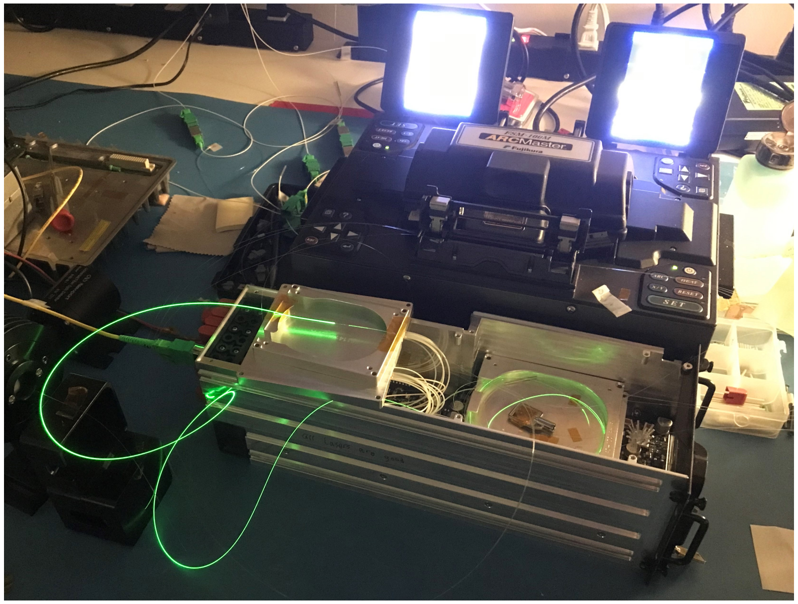


When $n_e \sim n_{cr}$, i..e $\omega_1 \sim \omega_p$

(E. Barraza)

Free-Space Laser vs. Fiber Laser



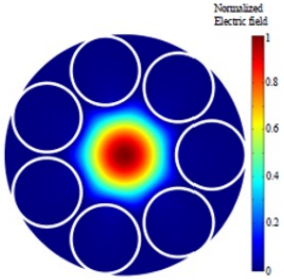


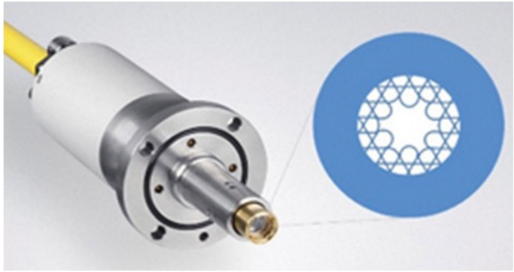
Fiber laser technology

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

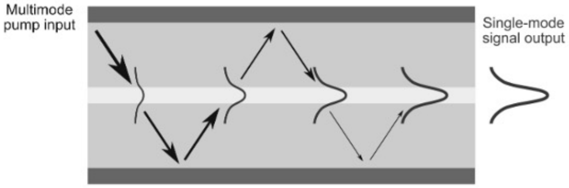


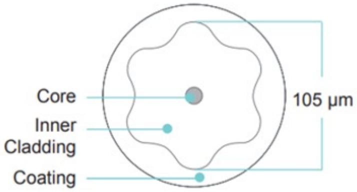


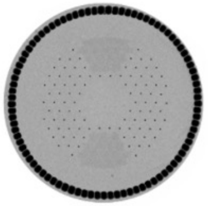
hollow fiber laser

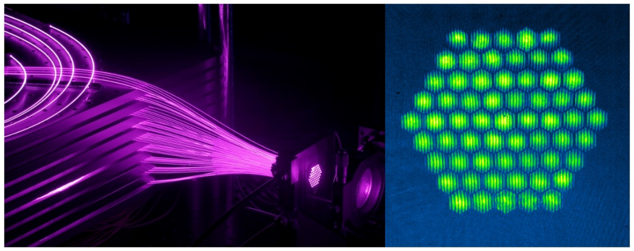
(Dr. W. J. Sha)

CAN fiber lasers









Conventional electron accelerator (and X-ray) for Therapy

Electron energies by accelerator: 6-20MeV

→ X-rays

LWFA could provide high dose “FLASH” therapy

Furthermore, much tinier with **fiber**

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

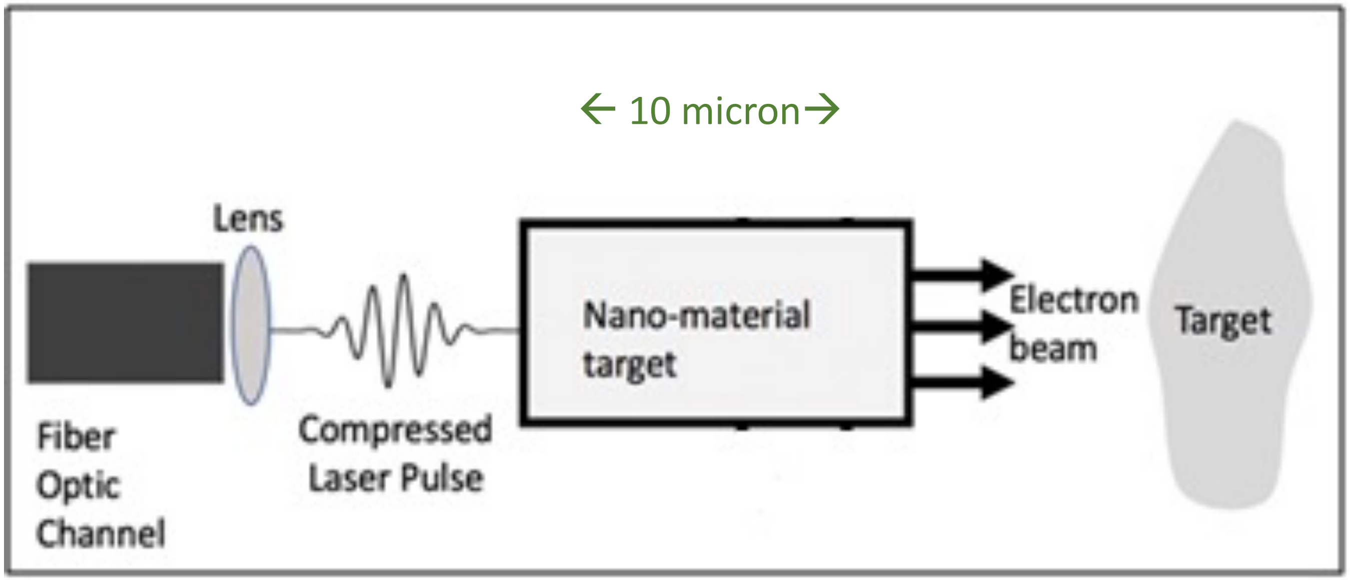
^ Body penetration

↑ Cancer cell size

← 5-10m (next room) →

(Varian)

In situ / endoscopic fiber delivery of electron radiotherapy of cancer



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

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

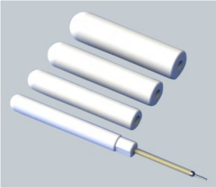
Cost **estimate** comparison with Brachy therapies

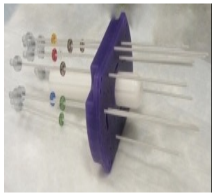
↓

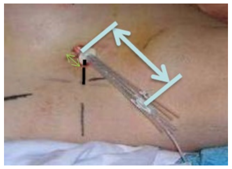
Item	**LWFA – HDR**	**Iridium-192–HDR**	**Cobalt-60–HDR**
Purchase Estimate	$100K - $300K	$700K - $900K	$700K - $900K
Room Shielding	None	$200K - $500K	$200K - $500K
Source Replacement	None	~$10K every 4-6 months	~130K every 60 months
Downtime due to Source Replacement	None	1-2 days	1-2 days

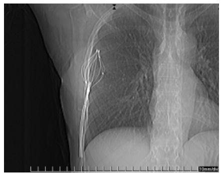
(Prof. D. Roa, preliminary estimate)

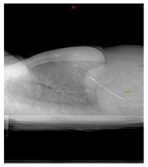
Current treatment applications (from skin, vagina, uterine, breast, etc.)

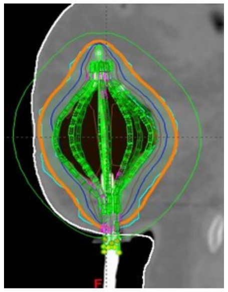


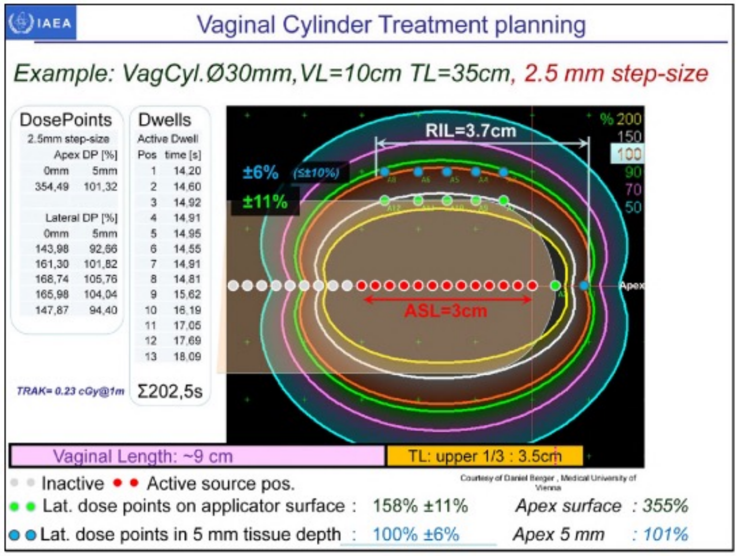












Vaginal Cylinder Treatment planning

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
Active Dwell

Pos	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

● ● Inactive ● ● Active source pos.

Courtesy of Daniel Berger , Medical University of Vienna

● ● 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

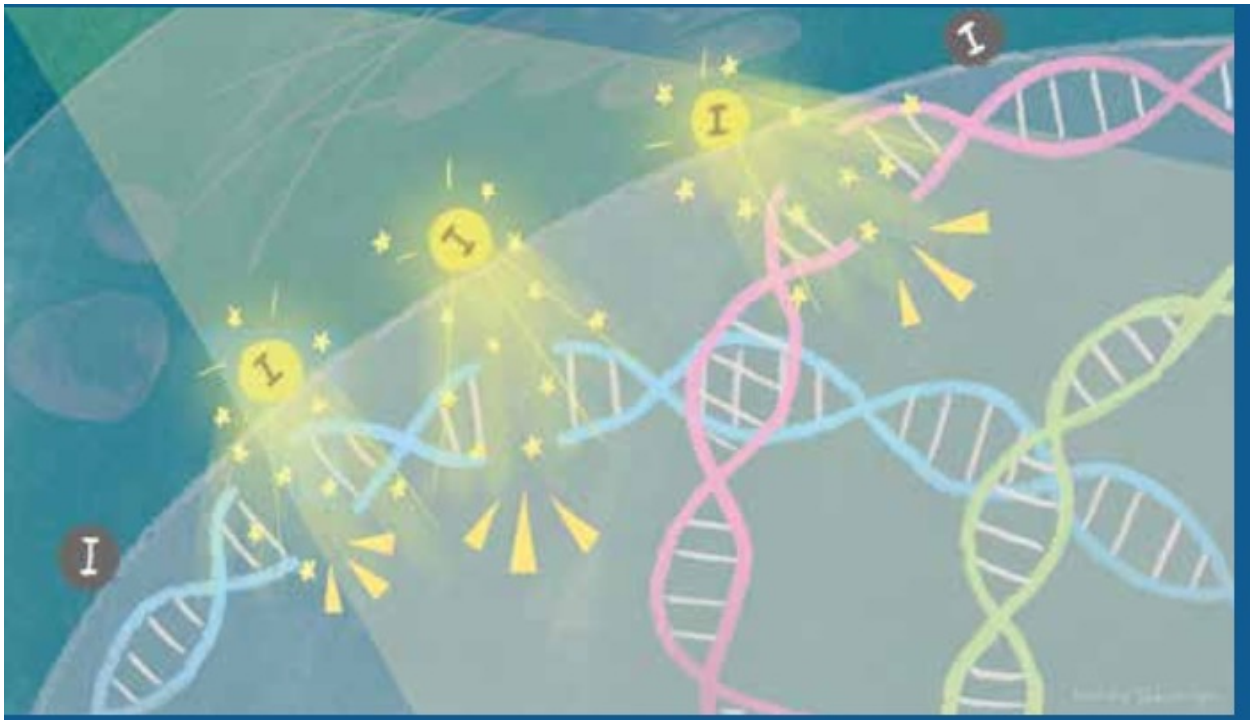
(Prof. D. Roa)

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)

Summary

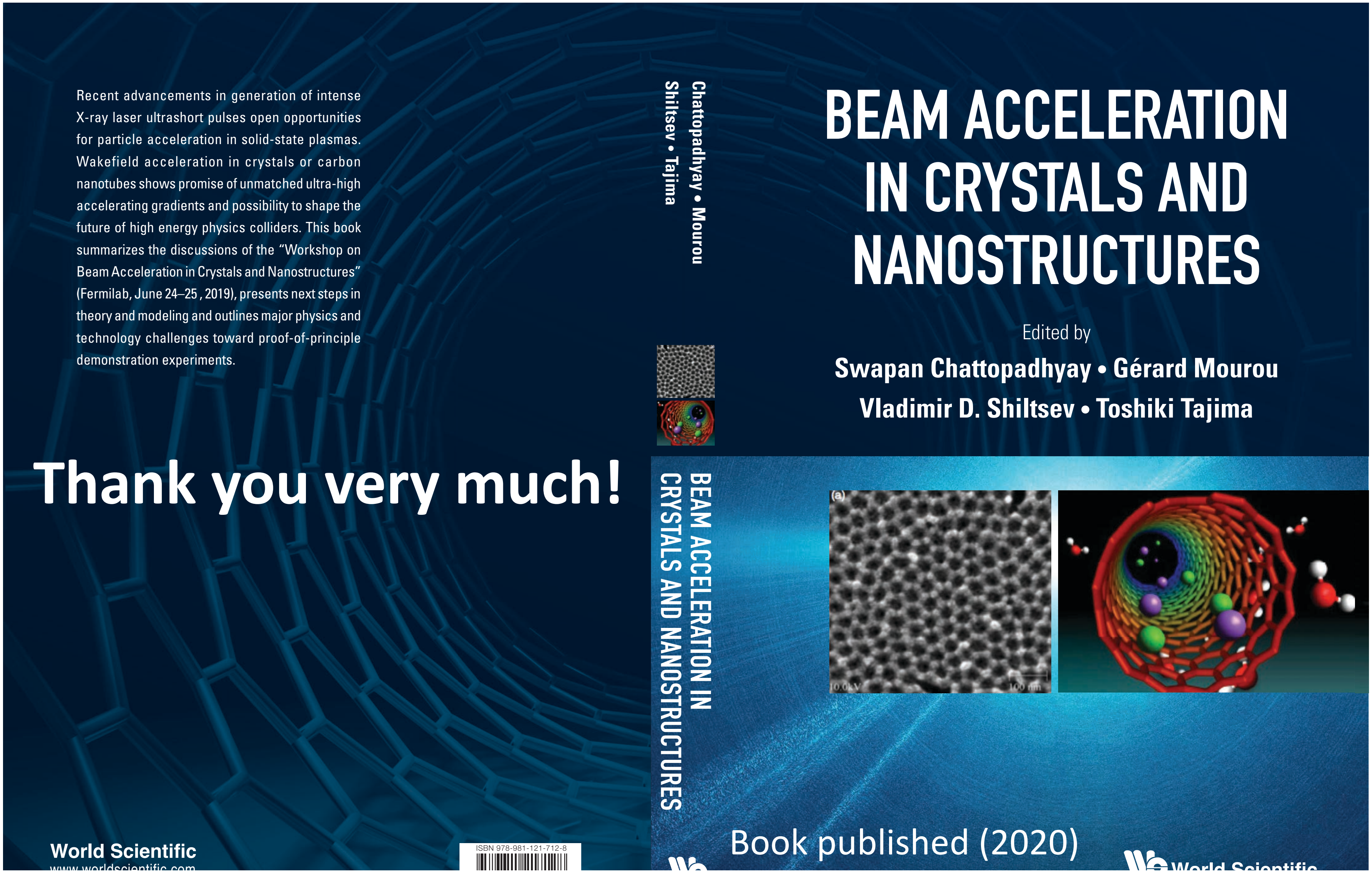
1. Near critical density (e.g. nanotube material) → low phase velocity LWFA

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
   ← replacing Brachy therapy

5. With nanomolecule vector (with high-Z particle attached),
   further accuracy, focus of electrons



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.

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Chattopadhyay • Mourou
Shiltsev • Tajima

BEAM ACCELERATION IN
CRYSTALS AND NANOSTRUCTURES

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

World Scientific

Thank you very much!

Book published (2020)

Appendix to p. 15: Conventional electron accelerator for radiotherapy