Conference on Lumiere et Laser, St. Martin de Pallieres, France (Aug.3, 2024)

Laser Wakefield Accelerators and their Applications to Medicine

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UCIRVINE

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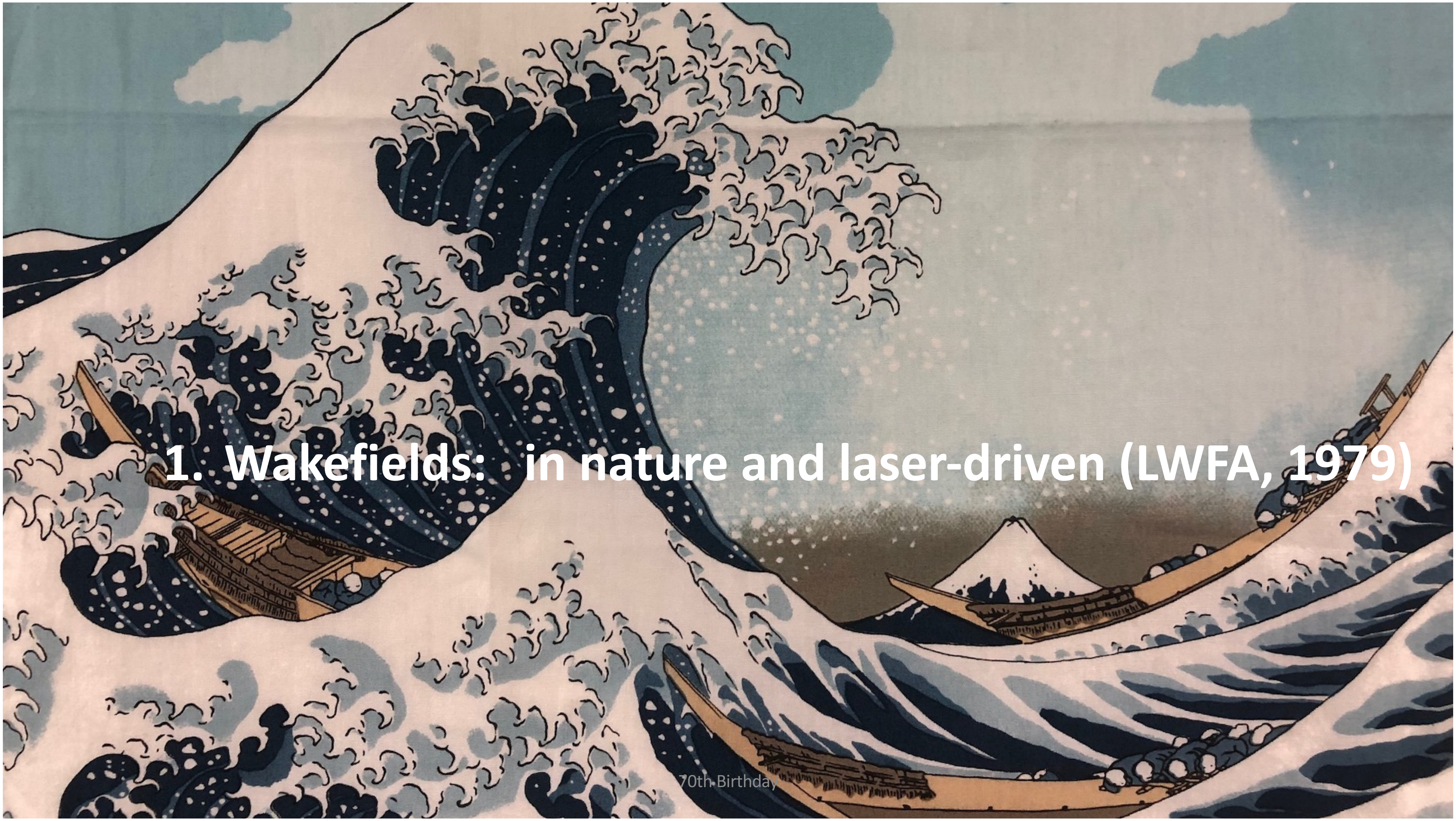


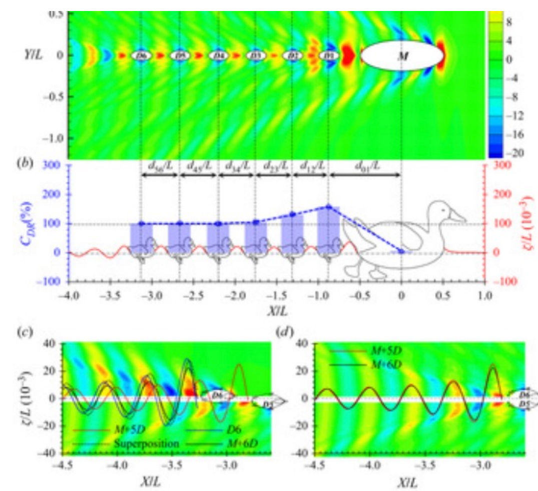
1. Wakefields: in nature and laser-driven (LWFA, 1979)

Wake

Wake by a duck on a lake:

Nature (or mother duck) shows us

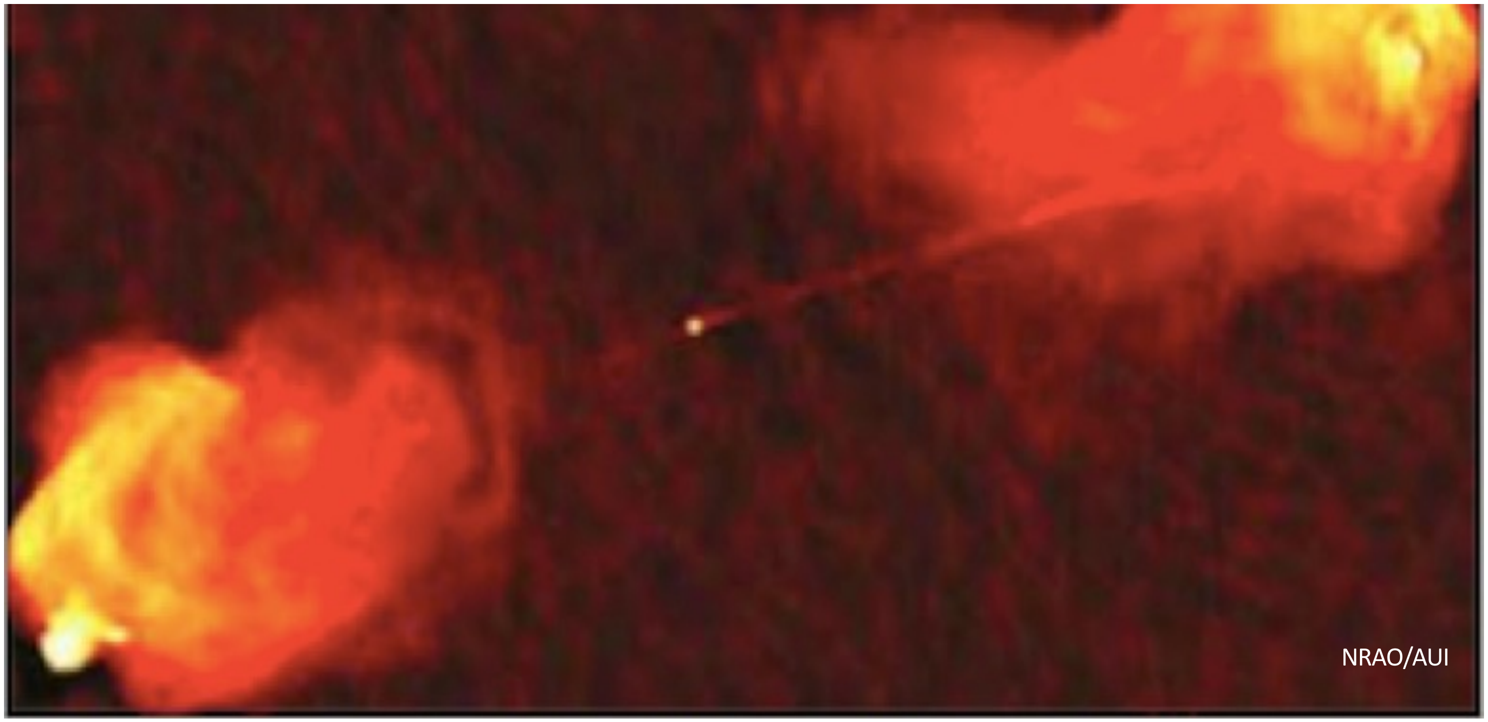
(since my undergrad times, 1969 at the Shinobazu- Pond, Tokyo).



Yuan et al. JFM (2021)

LWFA: Self-organized, Robust, Stable Structure with Huge Fields ← $v_{ph} >> v_{th}$

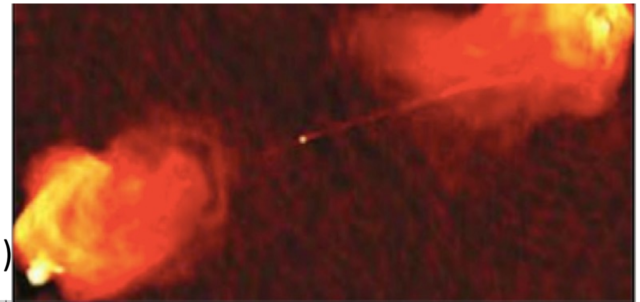
Mother Nature shows us:



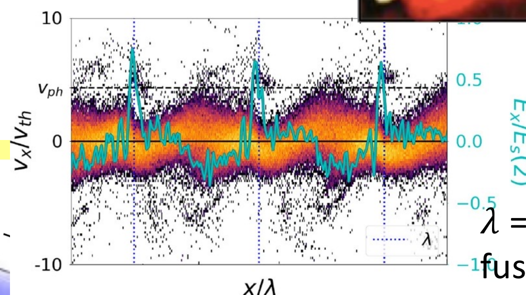
Ultra High Energy Cosmic Rays (UHECR) pinpointed from blasar (AGN) observed:
evidence for LWFA from the Universe (Ebisuzaki, Tajima, and Barish, 2023)

Ranges of wakefields

λ : 10^{-13} cm ← lab → 10^{19} cm

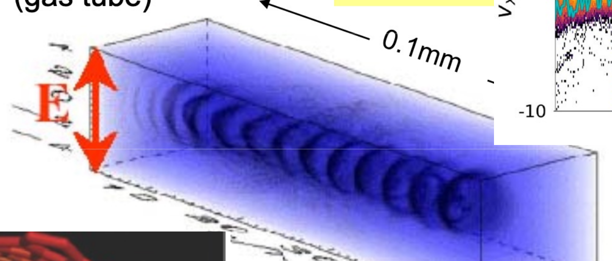


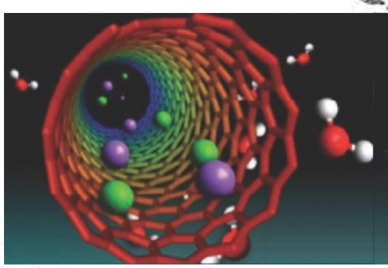
$\lambda = 10^{19}$ cm
(AGN jets and
UHECR, 2023)



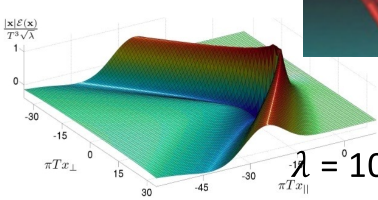
λ = 1 cm (beam-driven
fusion plasma, Nicks,
2021)

$\lambda = 10^{-4}$ cm (LWFA, 2004)
(gas tube)





$\lambda = 10^{-7}$ cm
Nanotube use for LWFA

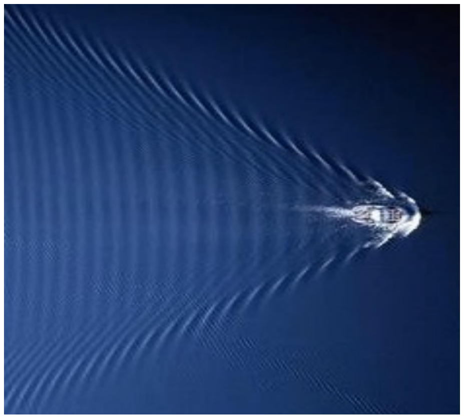


$\lambda = 10^{-13}$ cm (nuclear QCD plasma)

Laser Wakefield (LWFA):

Wake phase velocity v_{ph} >> water movement speed maintains **coherent** and **smooth** structure

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



vs

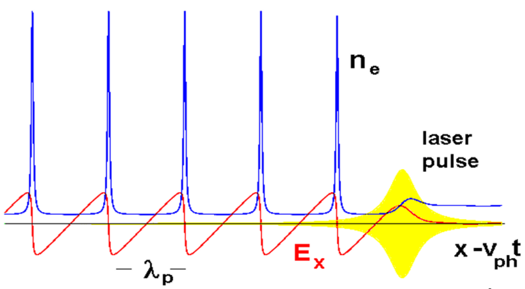
With low phase velocity

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 $v_{ph} \approx c$

Multiple of waves at $v_{ph} < c$



← relativity regularizes (*relativistic coherence*)

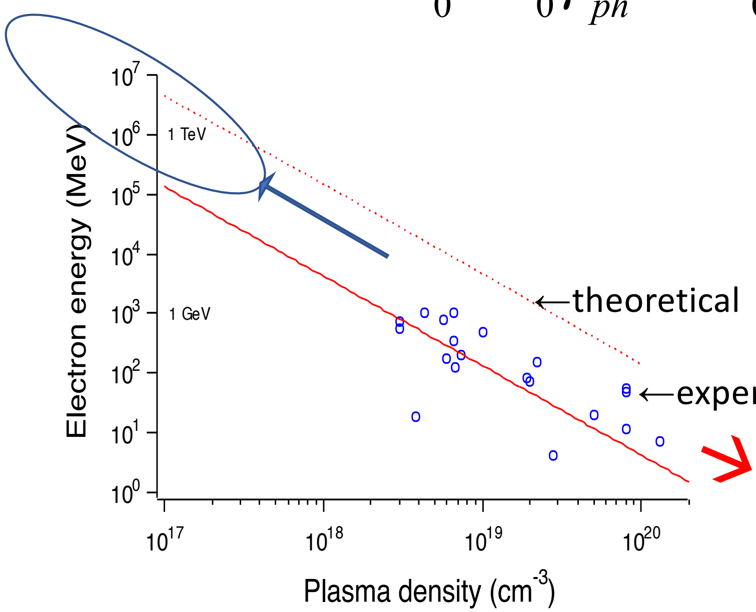
a_0 ~ 10 >> 1 (relativistic wave)

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

Theory of wakefield: photons to electrons
extreme high energies ←→ 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 = $10^{16\text{-}19}$ (gas) ⟶ 10^{21} /cc(porous solid)

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

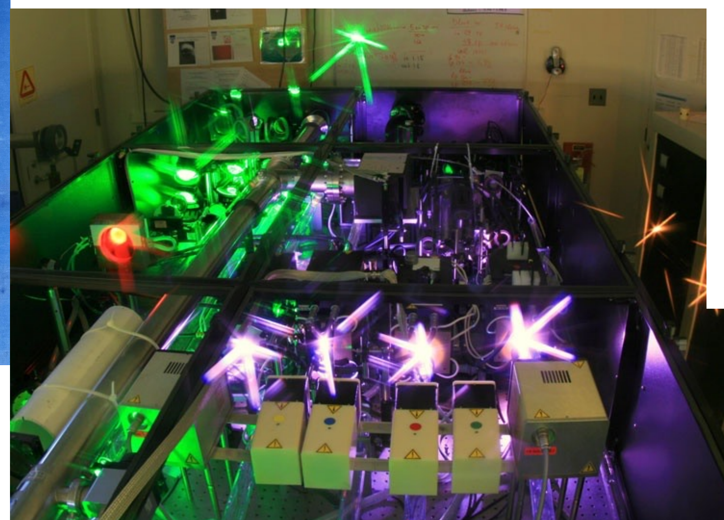
dephasing length

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

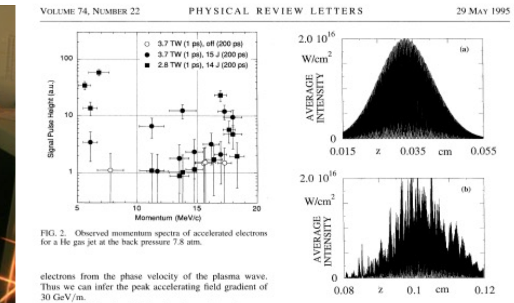
pump depletion length

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)

4 GeV laser accelerator LBL

3GeV Synchrotron SOLEIL

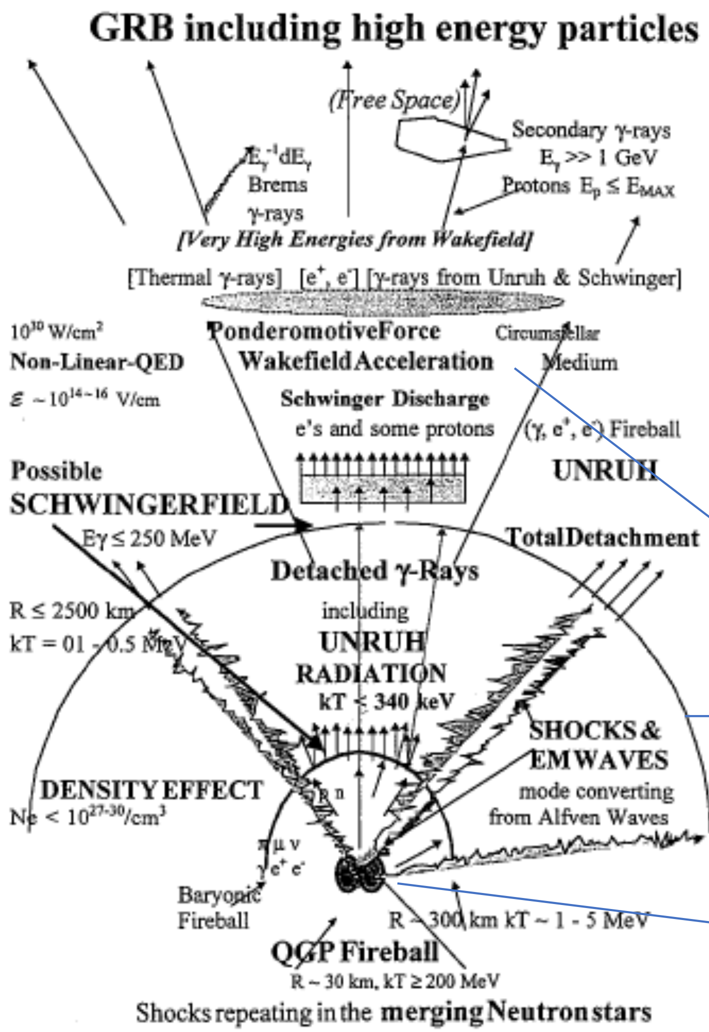


Figure 8. A schematic illustration of the proposed concept.

Cosmic Acceleration by LWFA

Prophetic picture (2000)

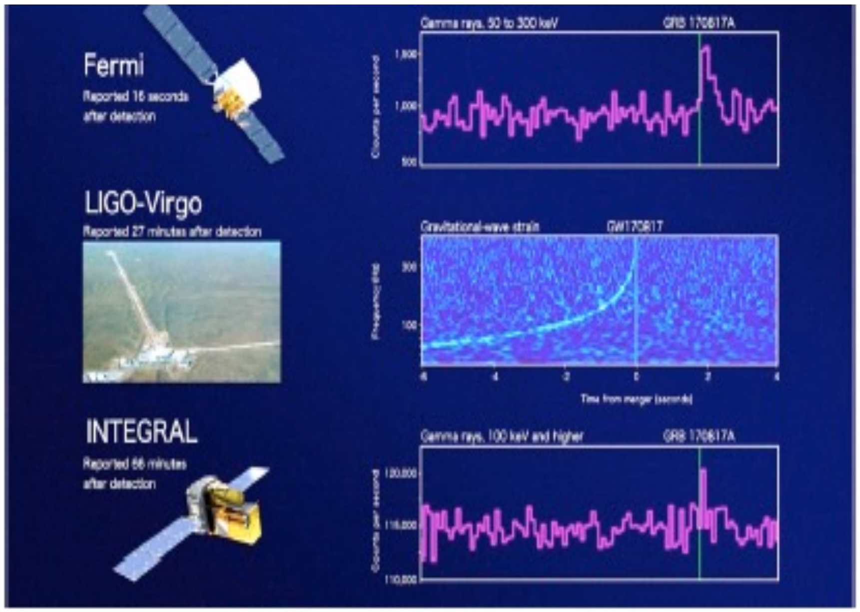
NS-NS collision
triggers→

- QGP (Quark-Gluon plasma)
- Shocks /**gravitational waves**
- Accretion disk
- Jets
- Alfven waves and EM waves
- **Wakefield acceleration**
- GRB (**gamma bursts**)
- ……
- Gravitational wave

→ see next page

Takahashi et al. (2000)

Wakefield acceleration by Neutron collision now observed



GW

Cosmic ray

Fig. 5. Gamma-ray emission detected by Fermi and Integral satellites from the neutron star merging event (GW178017) delayed by 1.7 seconds compared with gravitational wave burst [79]. This time difference may be explained by the time to build-up the system for the acceleration of charged particles, described in the present

Prediction (2000, Takahashi† and Tajima)
proved to be observed (2017, Barish's LIGO):

from accretion disk
and jets emanated from NS-NS collision →
GW emission and gamma emission (Nobel)

LIGO (2017)

(Laser Interferometric Gravitational wave Observatory)

T. Tajima B. Barish T. Ebisuzaki
at LIGO

Also **UHECR** (Ultra High Energy Cosmic Rays) emanated by **AGN** (Active Galactic Nuclei) (2014, 2023)

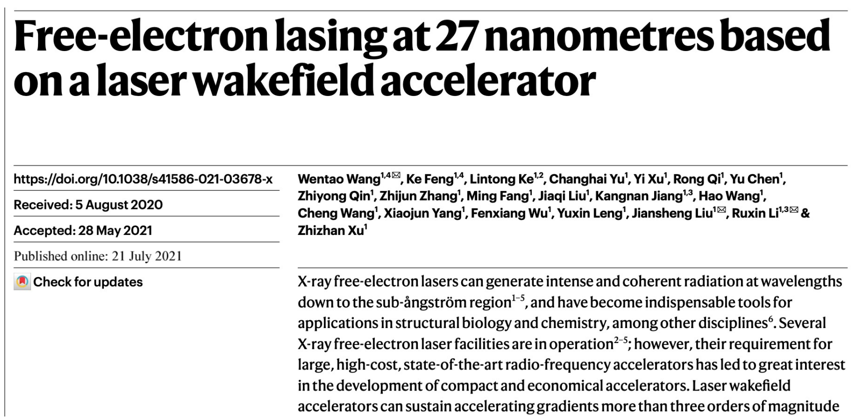
2. High energy LWFA → nonrelativistic LWFA→ medical FLASH (VHEE) therapy by LWFA

LWFA drives FEL X-rays (More recent firsts)

(beside the future laser-driven high energy accelerators)

1. Compact LWFA acceleration for various local needs for or with **beam sources** **(e.g. fusion reactors)**
2. Compact **X-ray FEL** using LWFA accelerators

   e.g. X-ray FEL amplified driven by LWFA, W.T. Wang et al., Nature (2020) [also Labat, et al., Nat. Phot.(2023)]



Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

https://doi.org/10.1038/s41586-021-03678-x

Received: 5 August 2020

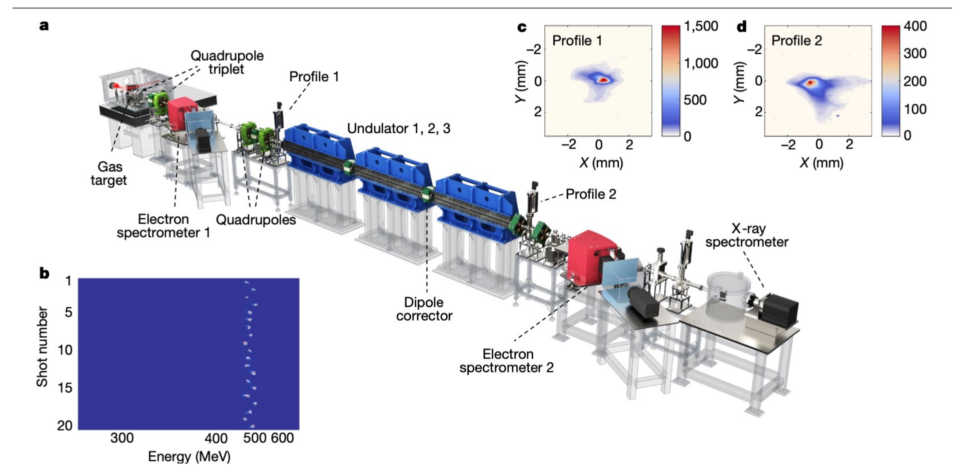
Accepted: 28 May 2021

Published online: 21 July 2021

Check for updates

Wentao Wang[1,4]✉, Ke Feng[1,4], Lintong Ke[1,2], Changhai Yu[1], Yi Xu[1], Rong Qi[1], Yu Chen[1], Zhiyong Qin[1], Zhijun Zhang[1], Ming Fang[1], Jiaqi Liu[1], Kangnan Jiang[1,3], Hao Wang[1], Cheng Wang[1], Xiaojun Yang[1], Fenxiang Wu[1], Yuxin Leng[1], Jiansheng Liu[1]✉, Ruxin Li[1,3]✉ & Zhizhan Xu[1]

X-ray free-electron lasers can generate intense and coherent radiation at wavelengths down to the sub-ångström region[1–5], and have become indispensable tools for applications in structural biology and chemistry, among other disciplines[6]. Several X-ray free-electron laser facilities are in operation[2–5]; however, their requirement for large, high-cost, state-of-the-art radio-frequency accelerators has led to great interest in the development of compact and economical accelerators. Laser wakefield accelerators can sustain accelerating gradients more than three orders of magnitude



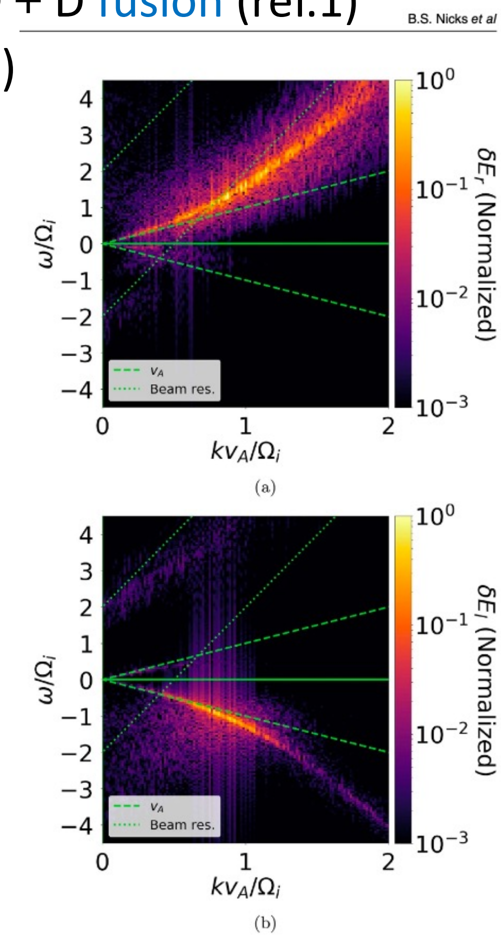
Now turn to the next application:

3. Compact **Flash electron radiotherapy** source by LWFA (see next pages)
4. LWFA at the **tip of endoscope:** even tinier electron source (see later pages)

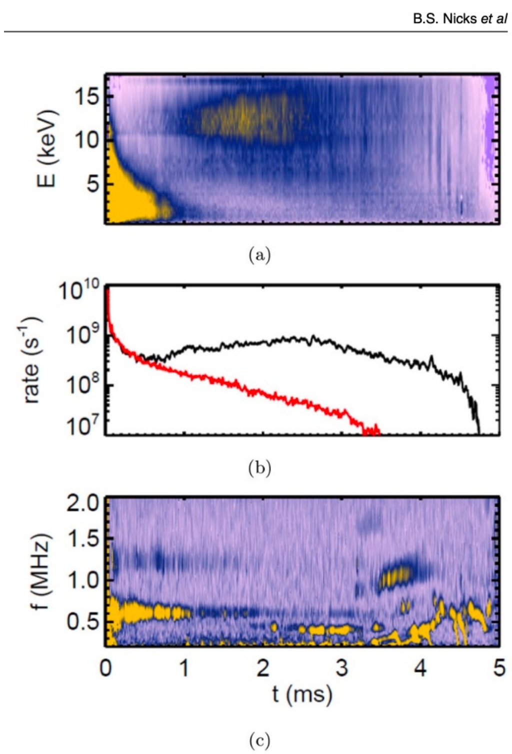
Wakefield acceleration in fusion plasmas (recent firsts)

Ion beam-driven wakefield drives fusion neutrons observation from D + D fusion (ref.1)

also fusion alphas from p + B^{11} fusion (ref.2)



Beam-excited waves →



← Neutron emission when **beam** is **on** (**black**)
and when beam is not on (red)

first evidence

Beam → wakefields → acceleration of tails → fusion

Ref.1 Magee, et al. Nature Phys. (2019)

Ref.2 Magee, et al., Nature Comm. (2023)

LWFA electron radiotherapy Flash (VHEE) : Realized

[based on the usual LWFA]

SCIENTIFIC REPORTS

OPEN

Focused very high-energy electron beams as a novel radiotherapy modality for producing high-dose volumetric elements

: 20 July 2018
: 1 July 2019
l online: 25 July 2019

K. Kokurewicz[1], E. Brunetti[1], G. H. Welsh[1], S. M. Wiggins[1], M. Boyd[2], A. Sorensen[2], A. J. Chalmers[3,4], G. Schettino[5,7], A. Subiel[5], C. DesRosiers[6] & D. A. Jaroszynski[1]

scientific reports

(2021)

OPEN

A focused very high energy electron beam for fractionated stereotactic radiotherapy

Kristoffer Svendsen[1]✉, Diego Guénot[1], Jonas Björklund Svensson[1,2], Kristoffer P
Anders Persson[1] & Olle Lundh[1]

An electron beam of very high energy (50–250 MeV) can potentially produce a more favo
radiotherapy dose distribution compared to a state-of-the-art photon based radiotherap
To produce an electron beam of sufficiently high energy to allow for a long penetration d
(several cm), very large accelerating structures are needed when using conventional radi
technology, which may not be possible due to economical or spatial constraints. In this p
show transport and focusing of laser wakefield accelerated electron beams with a maxim

Radiothérapie Flash : la recherche préclinique avance

MARDI 25 MAI 2021 Soyez le premier à réagir

La radiothérapie Flash, qui génère des rayonnements de très haute intensité en in temps très court, pourrait bi phase clinique. C'est ce qu'espèrent les chercheurs de l'Institut Curie qui travaillent sur ElectronFlash, une recherche expérimentale fournie par la société SIT.

L'Institut Curie et la société SIT ont récemment signé un premier projet conjoint de recherche dans le domaine de « Flash ».

Ils disposent aujourd'hui d'une plateforme de recherche expérimentale (ElectronFlash) performante, fiable et opérationr voie vers de potentielles applications cliniques de la radiothérapie Flash. Bien que l'imagerie, la balistique et la dosimétrie significativement ces dernières décennies, les technologies de délivrance des doses n'ont pas beaucoup évolué. N découvert il y a quelques années dans les laboratoires de l'Institut Curie par la délivrance de rayons à haute intensité dan courts ouvre un nouveau paradigme en radiothérapie.

L'Institut Curie effectue un gros travail de recherche sur cette technologie depuis 2019, en étroite collaboration avec la s conçu la plateforme de recherche expérimentale (ElectronFlash) installée sur le site de l'Institut Curie à Orsay. De nou *vitro* et précliniques sont en cours avant de passer en phase clinique. Il s'agira de déterminer les paramètres physiqu dispositif, de démontrer l'effet anti-tumoral de la radiothérapie Flash sur des modèles *in vitro* et précliniques et de prépare applications cliniques.

Le but de ces travaux est de faire émerger la prochaine génération d'accélérateurs de particules, notamment en ra opératoire, pour proposer des traitements moins lourds aux patients.

Paolo Royan

Réagir à cet article

Sur le même thème : Radiothérapie | Les plus lus | Les plus récents

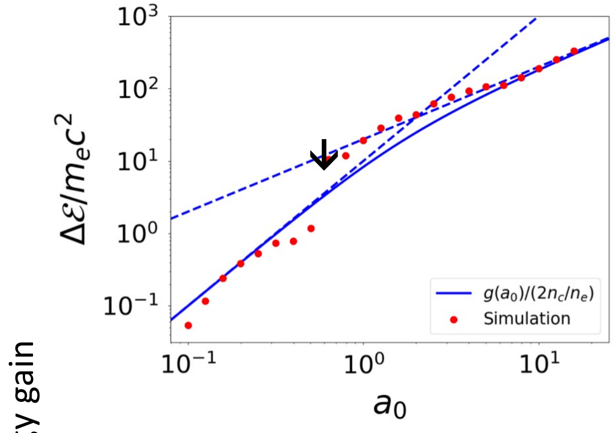
La SFRO élit un nouveau bureau pour les deux prochaines années
14/02/2024 : Le nouveau Bureau de la Société Française de Radiothérapie Onologique vient d'élire sa nouvelle en la personne du Pr Véronique Vendrely. Il s'inscrira dans la continuité des actions de l'équipe précédente et es de trois collèges (CHU/CHG - CCLC/ESPIC - SEcteur libéral).

3. Toward Microscopic LWFA, beat wave excitation

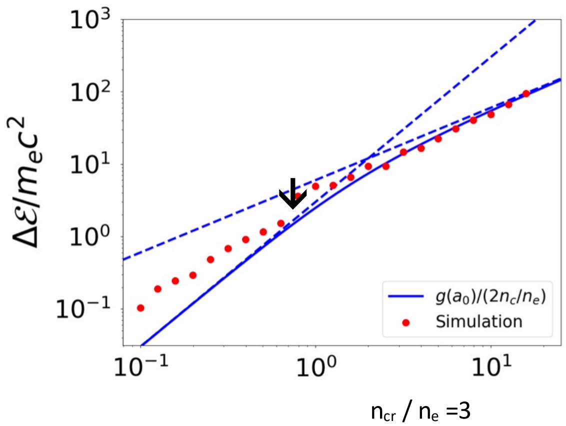
Exploration of Transition to $a_0 < 1$ regime and near-critical density $n_e \sim n_{cr}$

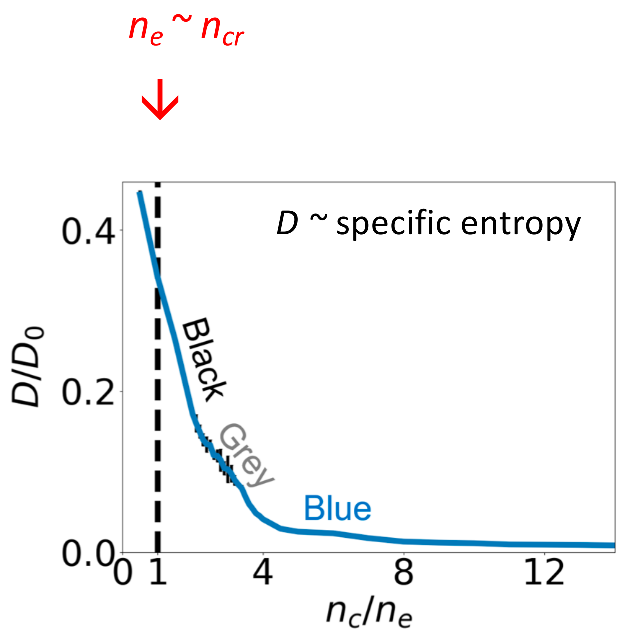
v_{gr} (group velocity of photon) = v_{ph} (phase velocity of plasma wave) << c

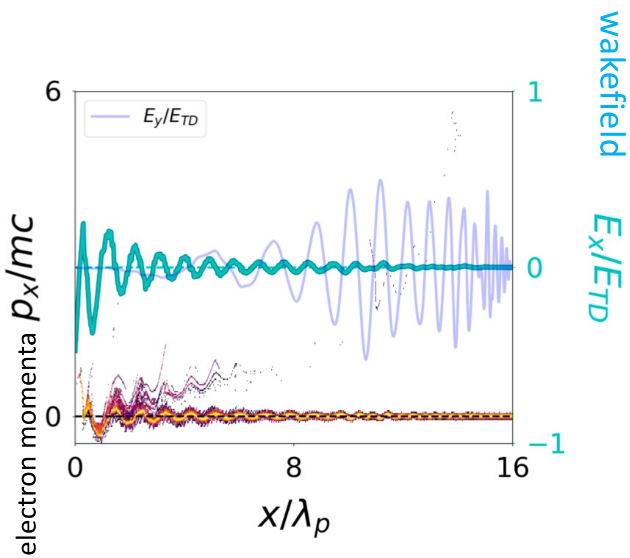
(S. Nicks, 2019)



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





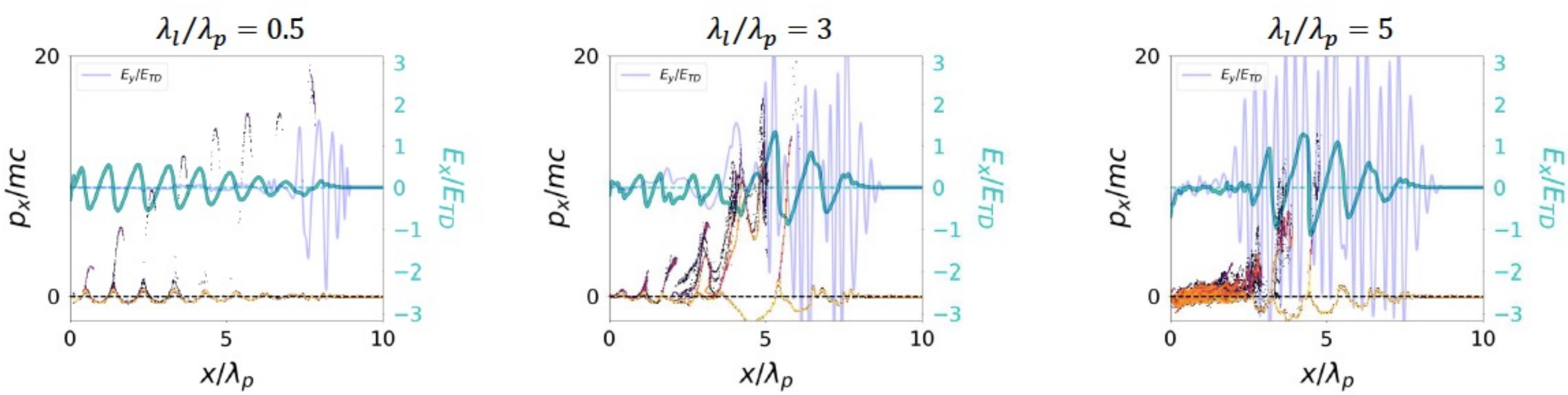


LWFA in low energy high-density regime

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

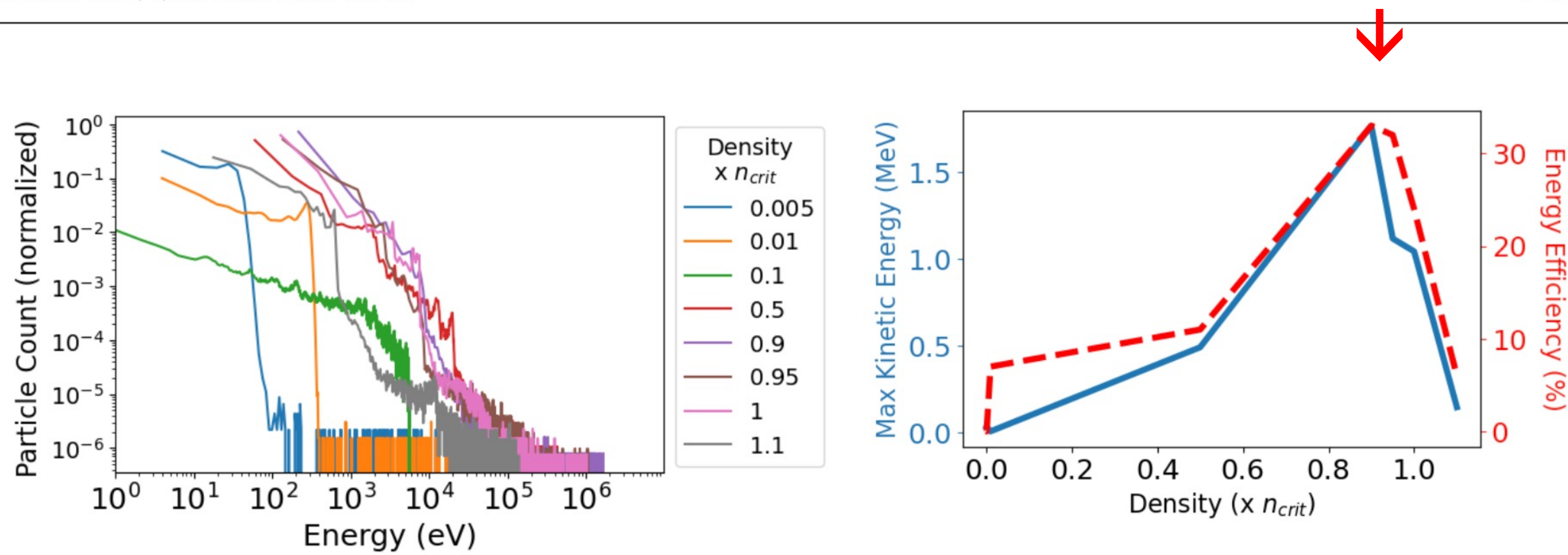
Self-Modulation

- 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)



(a) (b)

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_s, a_0 = 0.1, and pulsewidth of 100 fs. The seed laser wavelength was held at λ =1 μm

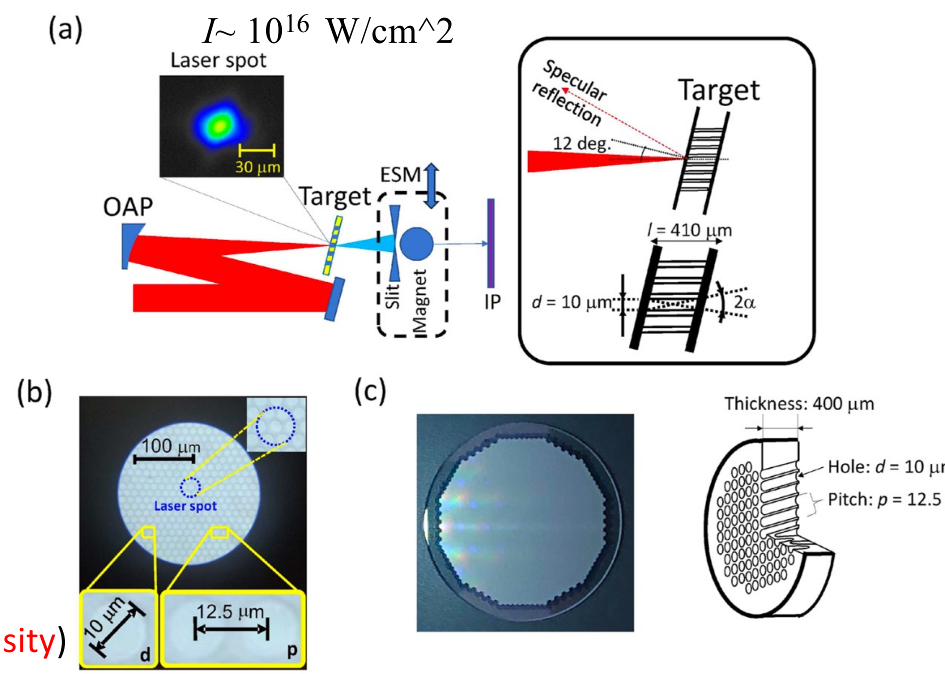
First Experimental Realization of LWFA in nonrelativistic regime in microcavity (2024)

AIP Advances ARTICLE pubs.aip.org/aip/adv

Experimental realization of near-critic laser wakefield acceleration: Efficient 100-keV-class electron beam generati by microcapillary targets

Cite as: AIP Advances 14, 035153 (2024); doi: 10.1063/5.0180773
Submitted: 17 October 2023 • Accepted: 29 December 2023 •
Published Online: 28 March 2024

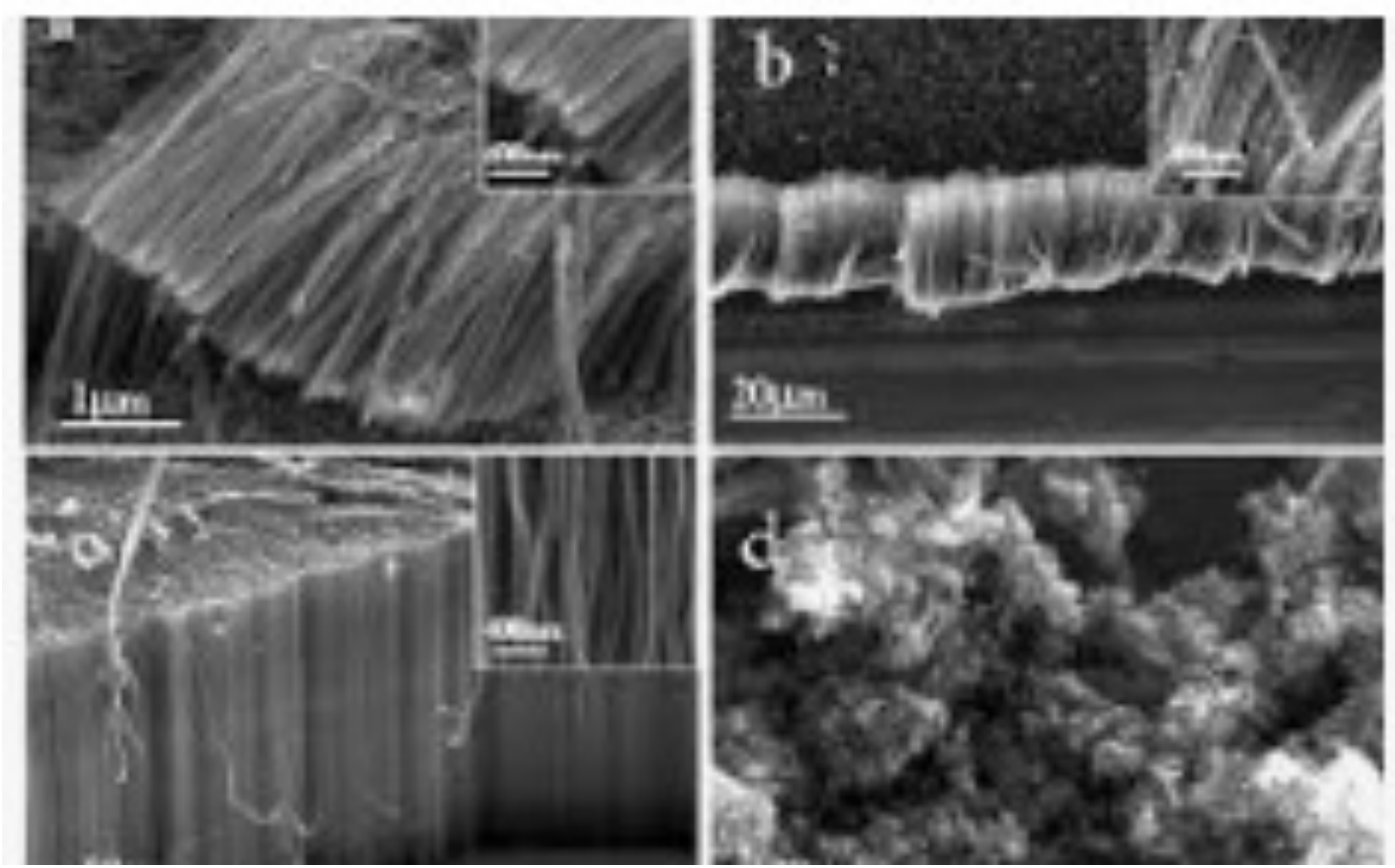
Michiaki Mori,[1,a)] Ernesto Barraza-Valdez,[2] Hideyuki Kotaki,[1] Yukio Hayashi,[1] M
Kiminori Kondo,[1] Tetsuya Kawachi,[3] Donna Strickland,[4] and Toshiki Tajima



(most efficient acceleration by LWFA happens near critical density)

Carbon nanotubes on a substrate:

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



Laser Wakefield Acceleration near critical density: Beat wave

gaseous plasma → nanotube

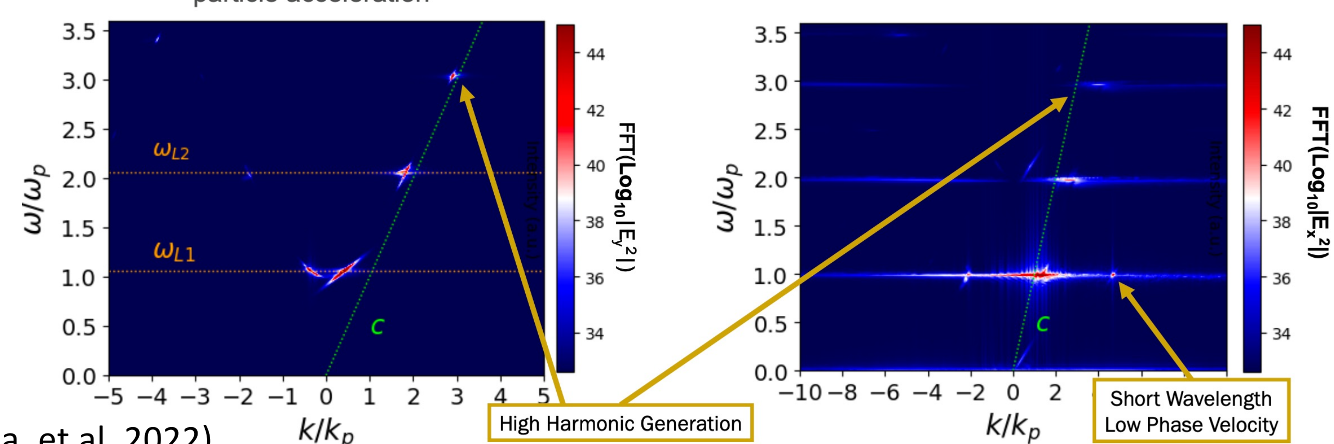
e.g. Bundle of packed nanotubes
with a few nm diameter
2μm thick target

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_{ph}
← curved laser $\omega\,(k)$, varied v_{gr}

Dispersion Relation: FFT(Log_{10}E)

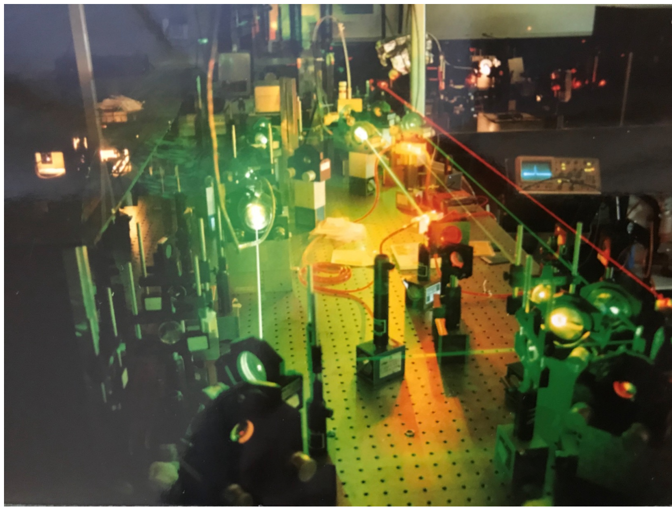
- High Harmonic Generation
- Short Wavelength and Low Phase Velocity Electrostatic Waves allow for more efficient particle acceleration



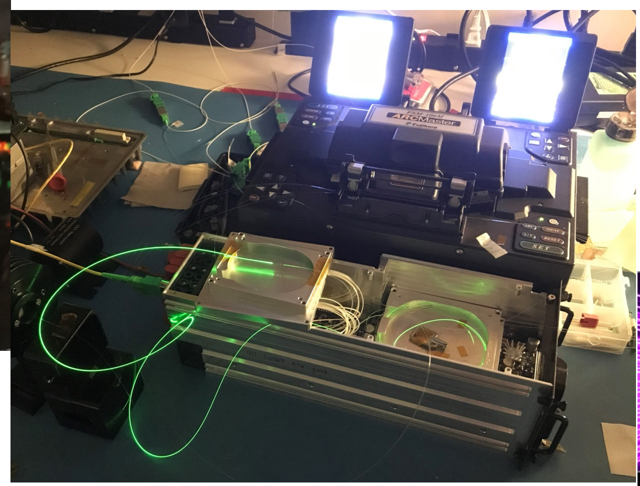
(Barraza, et al. 2022)

4. Fiber laser technology

Free-Space Laser vs. Fiber Laser

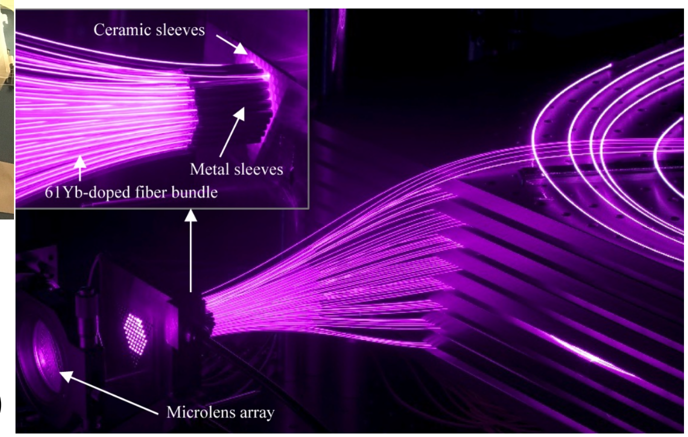


CPA laser
(LWFA stimulated CPA)



Fiber lasers

(See Dr. W. Sha's talk on Aug. 5, 2024)



(CAN fiber laser;
Prof. Chanteloup, Aug. 5, 2024)

Fiber laser technology

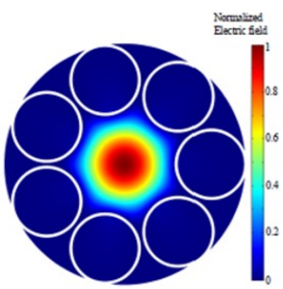
Application	Average Power	Pulse Width	Peak Power	Spatial Mode	Focused Intensity
Metal cutting (heat)	1 to 100 kW	Continous	same as average	MM	10^{7} W/cm^{2} (CW)
Semiconductor Processing	10 to 1000 W	1 to 100 ns	MW (10^{6} W)	MM/SM	10^{9} W/cm^{2} (peak)
Glass cutting (cold ablation)	> 10 W	≤ 0.5 ps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

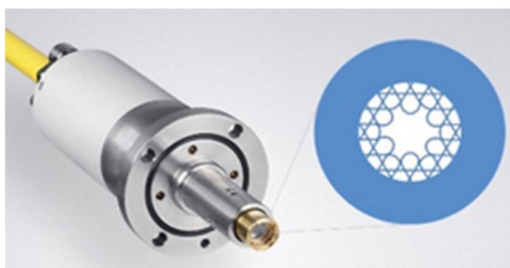
MM: multi-mode (spatial) SM: single mode

←

Under the collaboration with
Dr. Donna Strickland on going

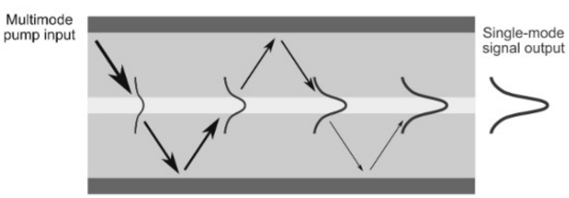
(Dr. W. J. Sh; Dr. J. Chanteloup)

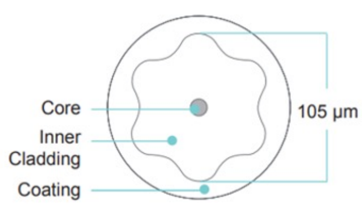


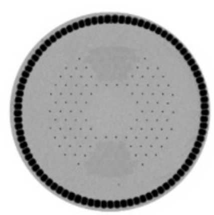


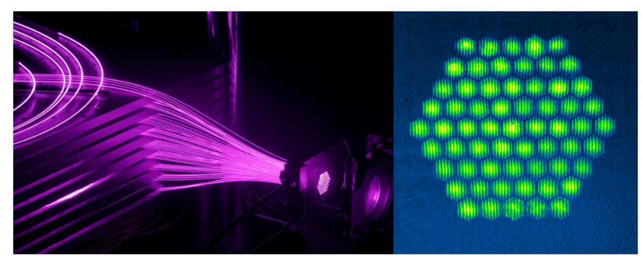
hollow core fiber laser
delivery

CAN fiber lasers









From Conventional electron accelerator (and X-ray) to Fiber Laser for Therapy

Electron energies by accelerator: 6-20MeV
(→ X-rays)

↓

LWFA provides high dose "FLASH" therapy

↓

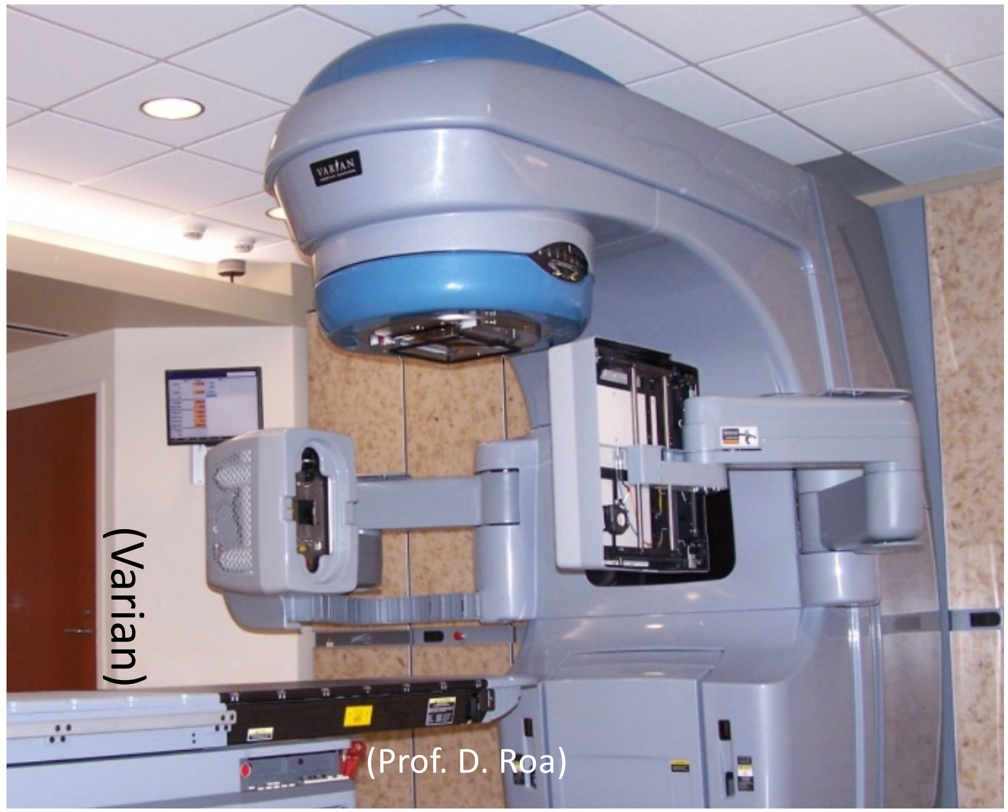
Furthermore, much tinier with **fiber**

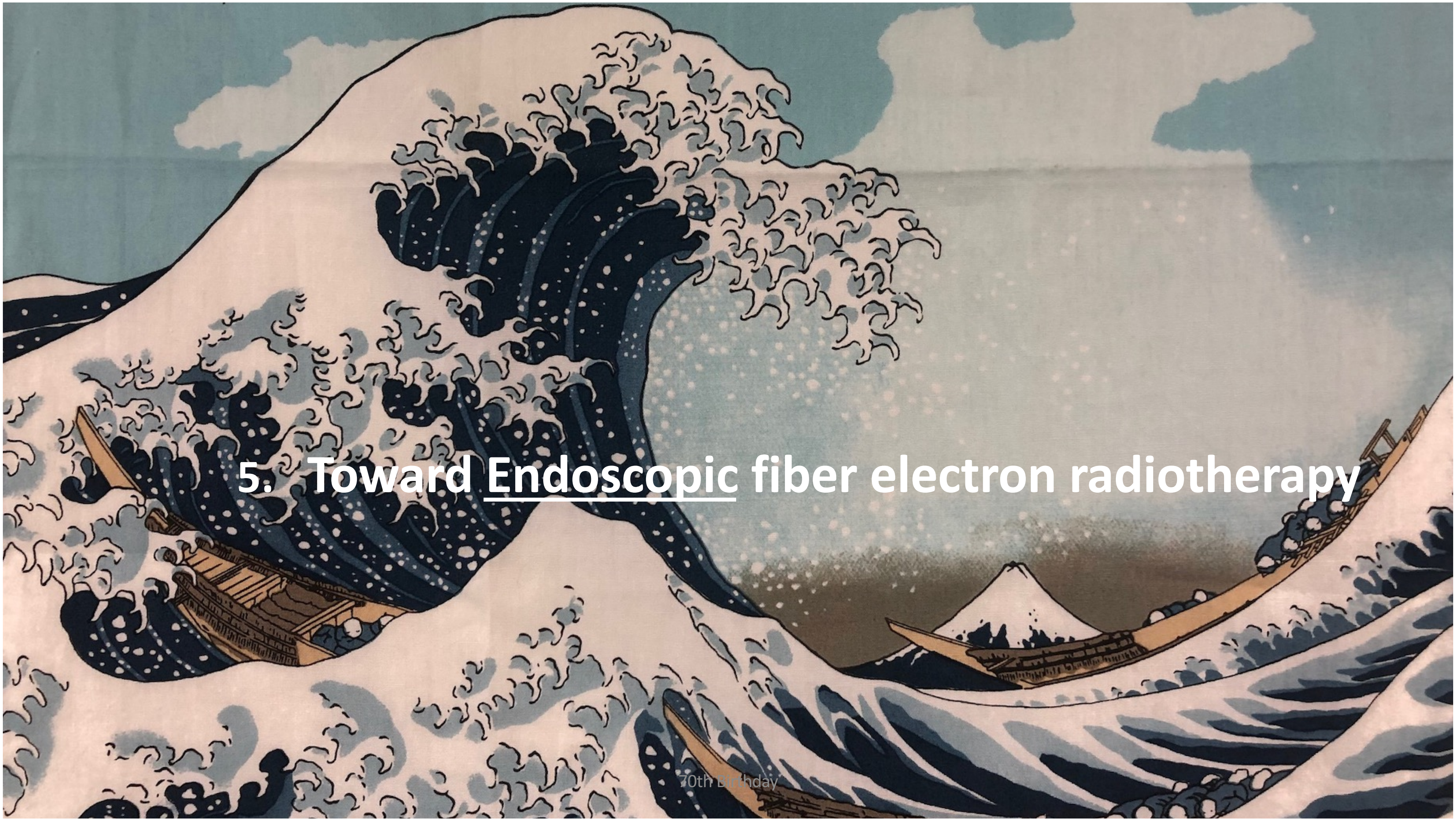
L_e ~ 1 cm / 10MeV → 10 micron / 10keV

^ Body penetration

↑ Cancer cell size

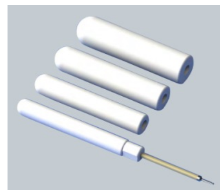
← 5-10m (next room) →

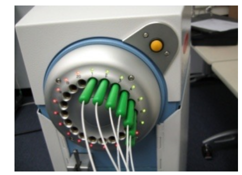
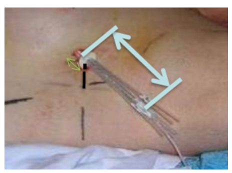


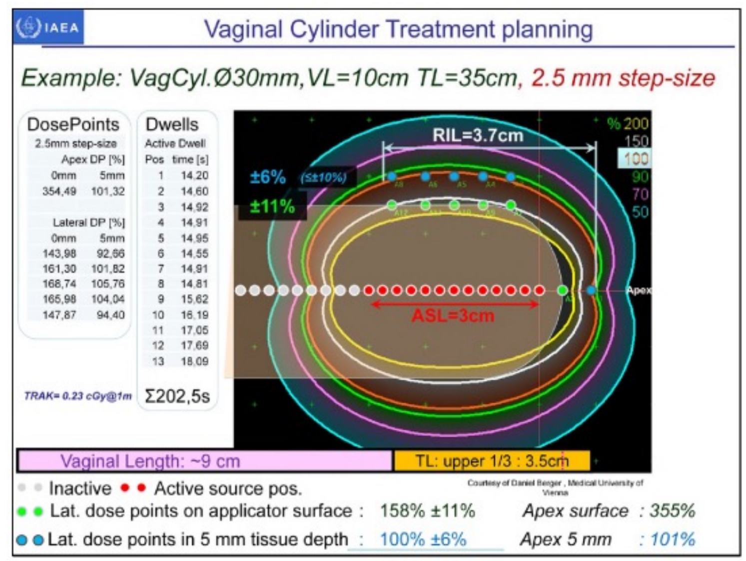


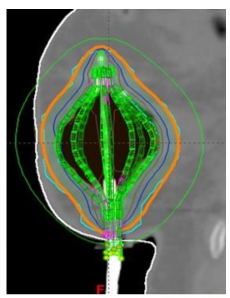
5. Toward Endoscopic fiber electron radiotherapy

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

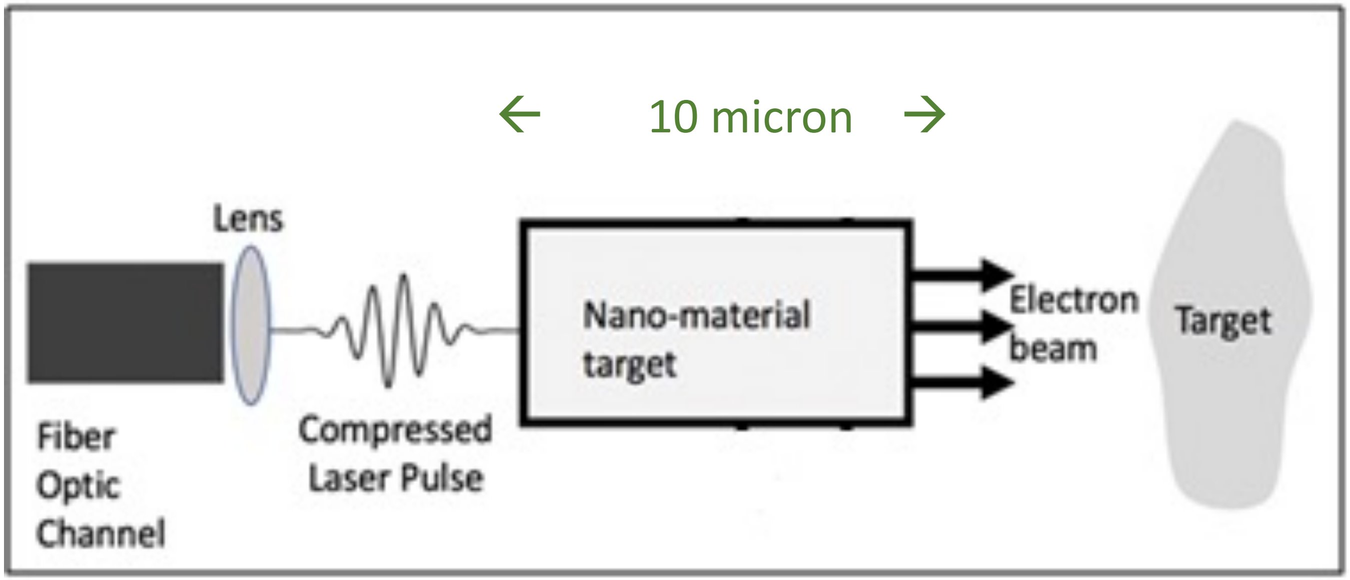



→ Much smaller, endoscopic in ours

(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**

(Dr. Sha, this workshop, 2024)

Cost **estimate** comparison with Brachy therapies

↓

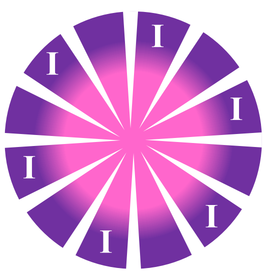
	LWFA – HDR	Iridium-192–HDR	Cobalt-60–HDR
Purchase Estimate	$100K - $300K	$700K - $900K	$700K - $900K
Room Shielding	None	$200K - $500K	$200K - $500K
Source Replacement	None	~$10K every 4-6 months	~130K every 60 months
Downtime due to Source Replacement	None	1-2 days	1-2 days

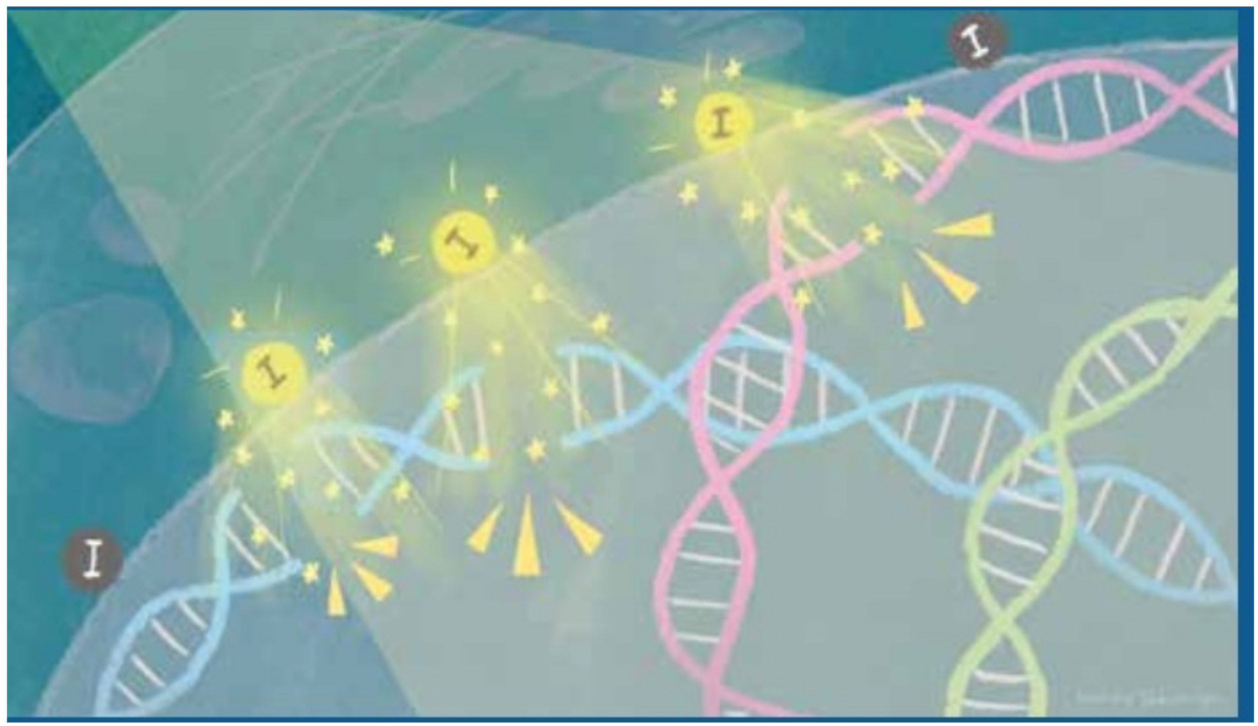
(Prof. D. Roa, preliminary estimate)

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 used for Auger electrons (after Prof. F. Tamanoi, Tajima, et al., 2022)

Summary

1. Laser wakefield: robust structure and strong compact acceleration

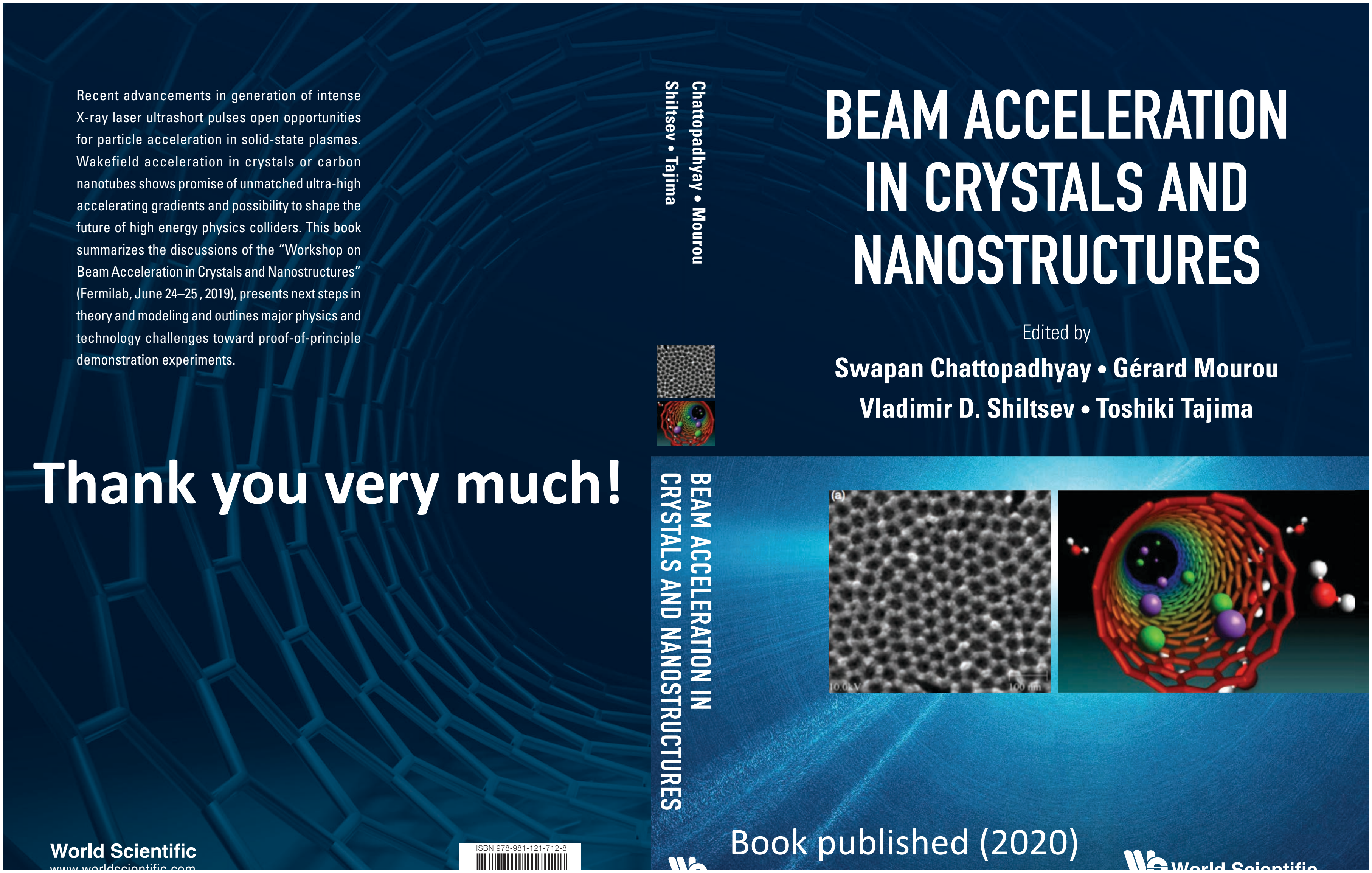
2. LWFA found in Universe and applied to FEL, Fusion, FLASH Therapy, etc.

3. Near <u>critical density</u> (e.g. nanotube material) → low phase velocity LWFA

4. Micron-scale low energy electrons (> 10keV, < MeV), with <u>fiber laser</u>

5. <u>Endoscopic</u> (through fiber) delivery of electrons for radiotherapy
   ← replacing Brachy therapy

Thank you very much!



Book published (2020)