Group Meeting (1/17/25)

CNT / Graphene and the Future of Fusion reactors and LWFA Applications to Medicine

T. Tajima

Department of Physics and Astronomy,

University of California at Irvine , CA, 92697 USA

Acknowledgements:

W. J. Sha, J. Kuo, D. Roa, D. Strickland, S. Nicks, E. Barraza,
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G. Kourimanou, P. Boulanger, K. Muramatsu, T. Kondo, X. Pan,
T. Massard

Table of contents

1. Background

Fusion reactor: the goal is getting closer (see my lecture notes of PHY249 "Physics of Fusion reactors" (April-June, 2024):

https://faculty.sites.uci.edu/tajima/teaching/

Now we need to consider: walls

2. Challenges of first wall

Fusion makes plasma hot → radiation such as X-rays (EM waves)

Fusion could make neutrons → neutrons are hard

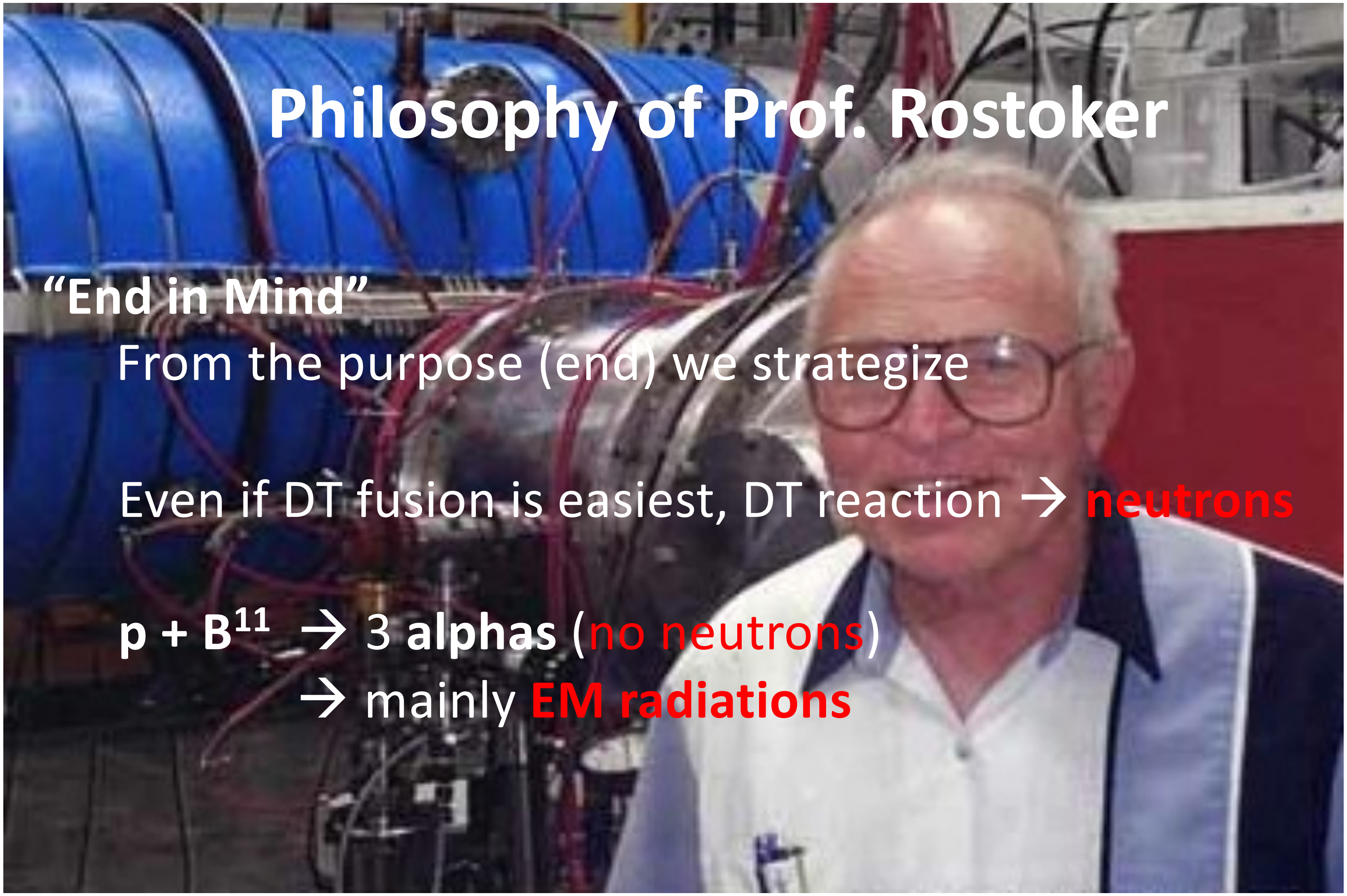
[we wish to avoid fuels that produce a lot of neutrons (s.a. DT → **pB^{11}**)]

3. Our choice of wall materials

low Z materials ← high Z materials absorb radiation and melt away

carbon in particular **CNT**, **graphene**

4. LWFA with CNT
5. LWFA with fiber laser
6. LWFA applied to endoscope (LWFA without vacuum)



Philosophy of Prof. Rostoker

"End in Mind"

From the purpose (end) we strategize

Even if DT fusion is easiest, DT reaction → **neutrons**

p + B^{11} → 3 **alphas** (no neutrons)

→ mainly **EM radiations**

Fast path to fusion reactors：Rostoker's philosophy

1. Fusion driven by **accelerator beams**

   [←instead of superhigh temperature heating of plasma]

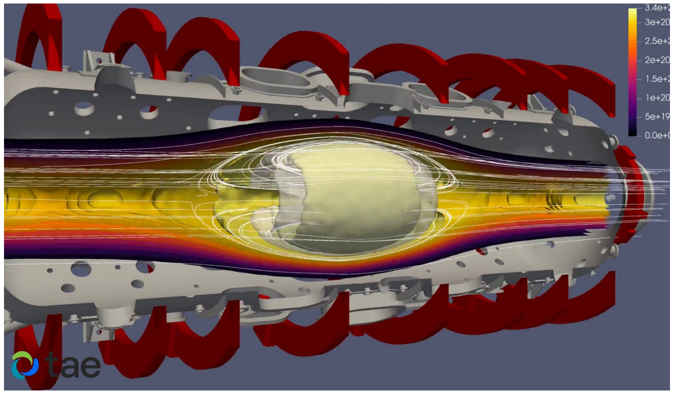
   If beam employed, it can be OK even for fuel that need 30times more temperatures for aneutronic fuel (pB11)　How can beams accelerated high energy ions?

2. Beam ring **stable FRC**, feedback AI controlled. **Ring of beams : stable and controllable**

3. Most fusion power in X-rays **directly converted** into electricity, only ~0.1% in neutrons

4. Superconductors: outermost layer (after small amount neutrons stopped)

FRC concept



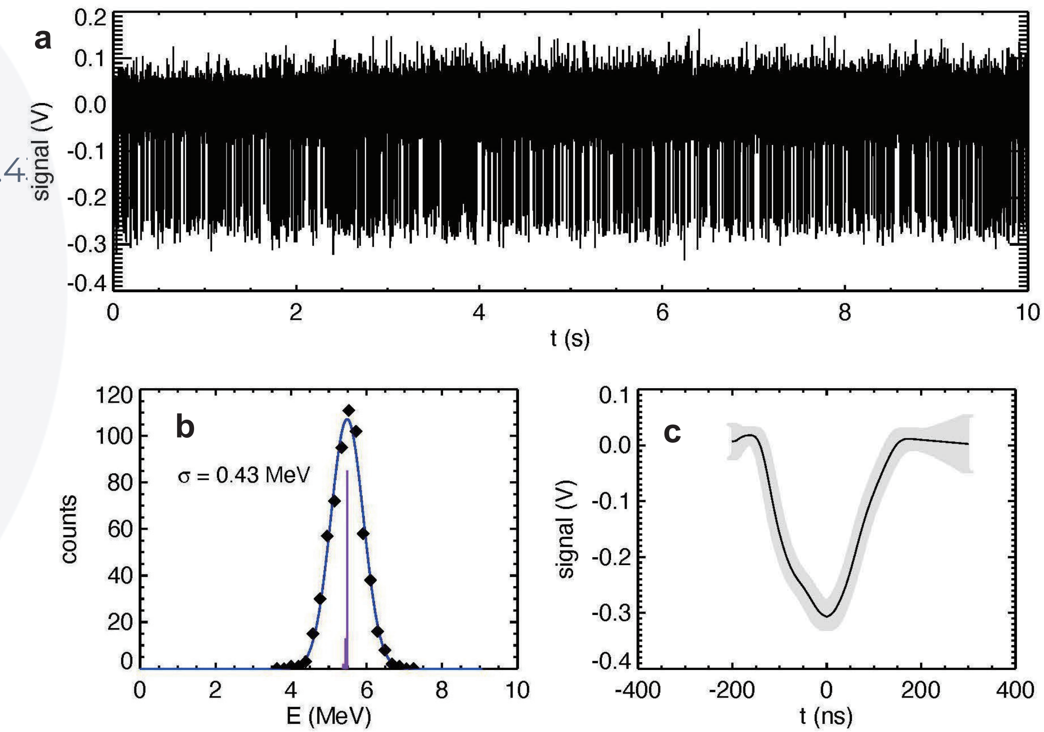
Norman Rostoker's **legacy** and **realization:**
FRC fusion plasma research machine called
"Norman"

← at the 4th floor lobby of
UCI Physics Department

First Experiment of **$p^{11}B$ Fusion** (2022)

Beams accelerated protons high energies

- Large number of pulses (~1000) averaged together for pulse shape discrimination
- Gives energy resolution of detector, σ = 0.4 MeV



Results Published in *Nature Communications*

nature communications

Article

https://doi.org/10.1038/s41467-023-36655-1

First measurements of $p^{11}B$ fusion in a magnetically confined plasma

Received: 4 November 2022

Accepted: 10 February 2023

Published online: 21 February 2023

Check for updates

R. M. Magee[1], K. Ogawa[2], T. Tajima[1,3], I. Allfrey[1], H. Gota[1], P. McCarroll[1], S. Ohdachi[2], M. Isobe[2], S. Kamio[1,3], V. Klumper[1,3], H. Nuga[2], M. Shoji[2], S. Ziaei[1], M. W. Binderbauer[1] & M. Osakabe[2]

Proton-boron ($p^{11}B$) fusion is an attractive potential energy source but technically challenging to implement. Developing techniques to realize its potential requires first developing the experimental capability to produce $p^{11}B$ fusion in the magnetically-confined, thermonuclear plasma environment. Here we report clear experimental measurements supported by simulation of $p^{11}B$ fusion with high-energy neutral beams and boron powder injection in a high-temperature fusion plasma (the Large Helical Device) that have resulted in diagnostically significant levels of alpha particle emission. The injection of boron powder into the plasma edge results in boron accumulation in the core. Three 2 MW, 160 kV hydrogen neutral beam injectors create a large population of well-confined, high -energy protons to react with the boron plasma. The fusion products, MeV alpha particles, are measured with a custom designed particle detector which gives a fusion rate in very good relative agreement with calculations of the global rate. This is the first such realization of $p^{11}B$ fusion in a magnetically confined plasma.

The proton–boron fusion reaction ($p^{11}B$),

$$p(^{11}B, \alpha)\alpha\alpha + 8.7\,\text{MeV} \quad (1)$$

has long been recognized as attractive for fusion energy[1]. The reactants, hydrogen and boron, are abundant in nature, non-toxic and non-

While the challenges of producing the fusion core are greater for $p^{11}B$ than DT, the engineering of the reactor will be far simpler. The enormous fluence of 14 MeV neutrons from a DT reactor plasma ($\sim 10^{19}$ n/m²/s) will require advanced, yet-to-be-developed materials for the first wall, threaten the integrity of superconducting coils, and necessitate remote handling of activated materials. None of these

- Statistics (as of 04/13/2023):
  - 17,000 views
  - 99th percentile for online attention in all journals tracked by Altmetric
  - 38 news articles (including Science, Phys Org, Physics World) in multiple languages

heise online

Kernfusion mit Bor und Protonen in Stellarator gelungen
Heise, 08 Mar 2023
TAE Technologies will nicht nur einen kommerziellen Fusionsreaktor bauen, der deutlich vor dem

tivi

Fuusioenergiassa läpimurto – Yhdysvaltalainen yhtiö testasi pb11-fuusiota stellaraattori-reaktorissa 5.3. 22:05Energia
Tivi, 05 Mar 2023
Yhdysvaltalainen kapallista fuusioteknologiaa kehittävä TAE Technologies on onnistunut

La fusion contrôlée aneutronique alternative à Iter marque un nouveau point !
Futura-Sciences, 03 Mar 2023
En 2021, l'ancien directeur général de l'organisation IterIter (rappelons que la Chine, l'Union européenne, l'Inc

ZDNet Japan

磁気閉じ込め核融合プラズマにおける水素化ホウ素核融合の初観測
ZDNet Japan, 06 Mar 2023
AsiaNet 99694 ネイチャー コミュニケーションズ誌で公表された最新の研究によると、クリーンて
るとのこと フットヒルラン

elperiódico de la energía

El hidrógeno-boro, el combustible que acerca de verdad la fusión nuclear
El Periódico de la Energía, 04 Mar 2023
Mientras los desarrolladores de fusión de todo el mundo compiten por comercializar la energía de fusión, la empresa TAE...

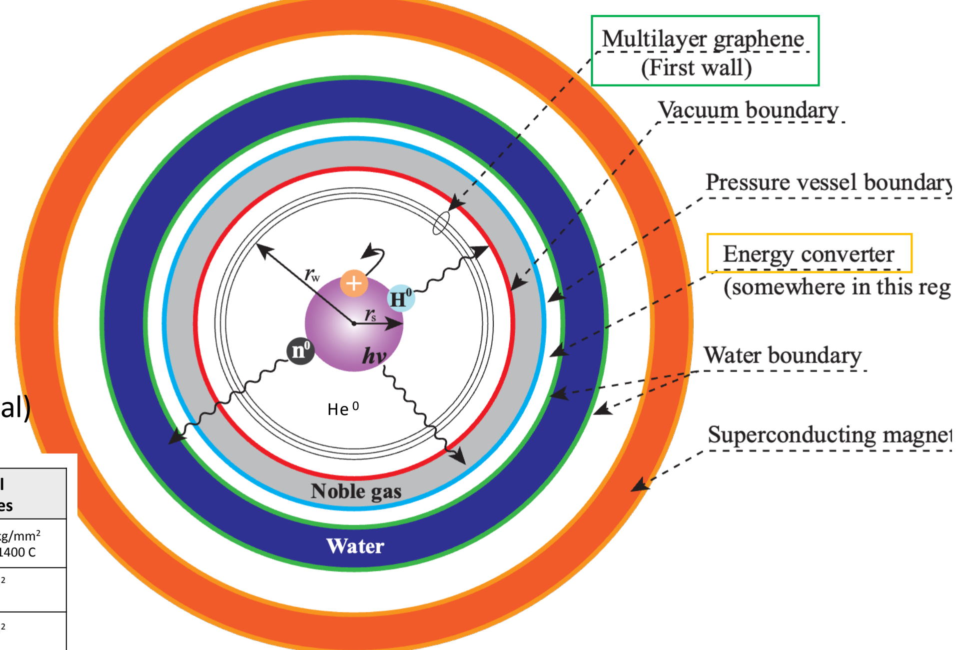
Characteristics of aneutronic fusion reactor

→ energy transfer by photons

direct energy conversion of photons

Concept/steps:

1. Xe (or other noble) gas cell irradiation
2. Auger electron emissions
3. Energy extraction of Auger electron
4. Electricity conversion system (e.g. diode system)
5. Carbon negative reactor (w/ proper first wall material)



Example/options of first-wall material

Severity of radiation on metals: Stainless Steel 304, Inconel 601, Hastelloy-N

Relative resilience of carbon materials: Carbon composites, Graphite, Diamond

Materials	Neutron damage [dpa/yr]	Neutron activation [Bq/cm^3]	Corrosion	Physical properties
Stainless Steel 304	1	2.0124 10^{11}	53 µm/yr	Hardness =140 kg/mm^2 Melting point=1400 C
Inconel 601	0.9	5.2081 10^{10}	> 34 µm/yr	77 kg/mm^2 1400 C
Hastelloy-N	1.2	1.6824 10^{11}	8 µm/yr Corr. attacks Cr	60 kg/mm^2 1320 C
Carbon composites	**0.12** Maintained structural integrity up to 32 dpa	**1.1959 10^9**	**Extremely low** – nm/yr?	**2600 kg/mm^2** **2700 C**
Graphite (reactor grade graphite)	**0.0013**	**1.6358 10^3**	**No attack by salt** 2.5 years of operation	Low < 40 kg/mm^2 3600 C
Diamond	**Very low** (for detectors) No data for wall, but should be even better!	**Only fast neutrons**, in reaction n+^{12}C->alpha+^{9}Be	**Extremely chemical inert**	**see diamond slide**

Dimond :chemical stability, low neutron activation and low neutron damage: Graphite : many good properties

T. Tajima and T. Massard, *Bio-inspired materials for the energy challenge of the Century*, https://hal.science/hal-04213307

Charged particles: confined by strong magnetic field

Neutrals: need to stop around the first wall

Neutrons: shielded by a layer of water

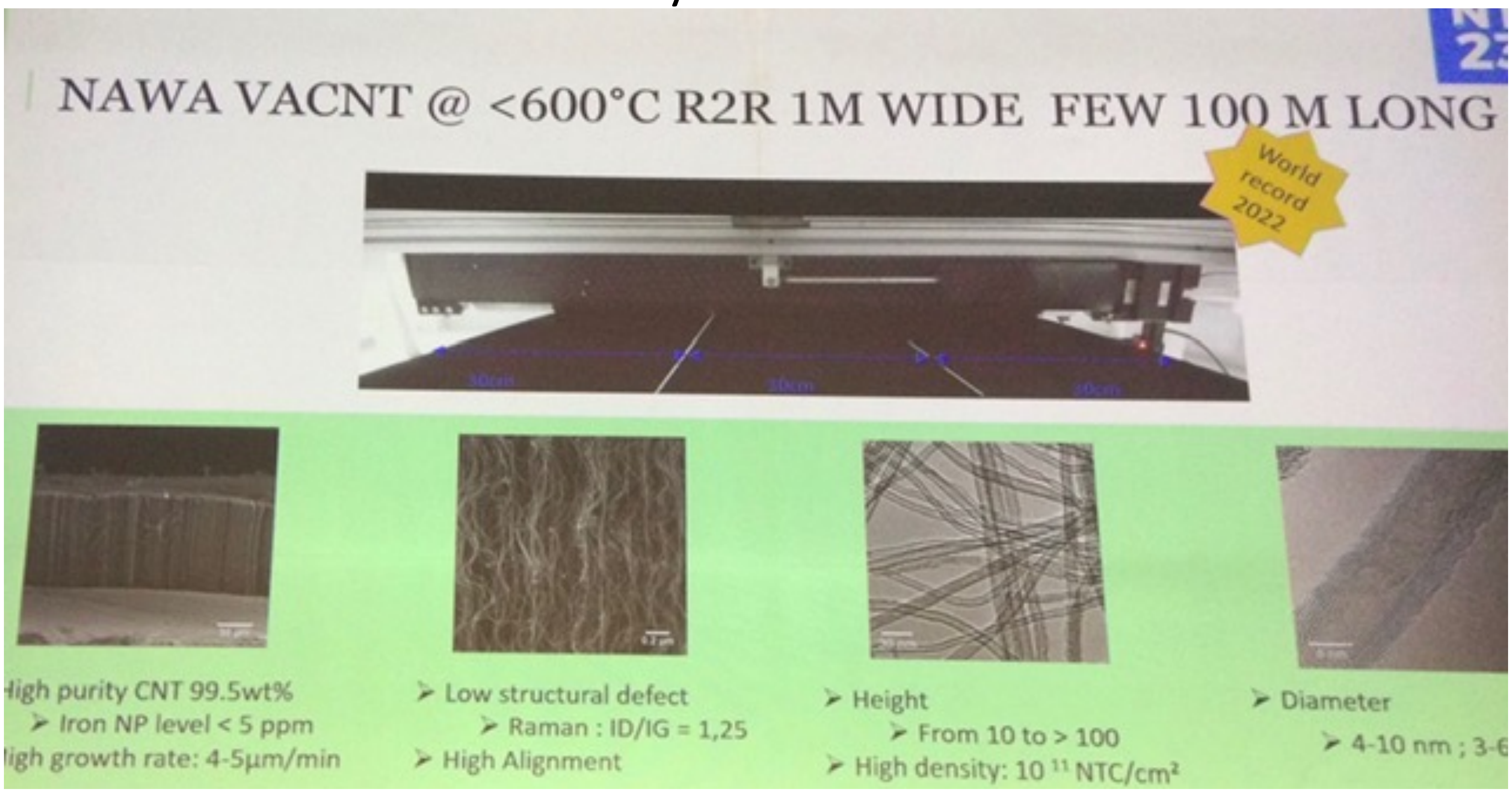
Photons: It is necessary to transport to the energy converter with high transmittance with minimizing damage to the first wall.

He^0: Go through, thus little chance for brittling

Fusion reactor needs CNT, graphene

for wall and energy conversion

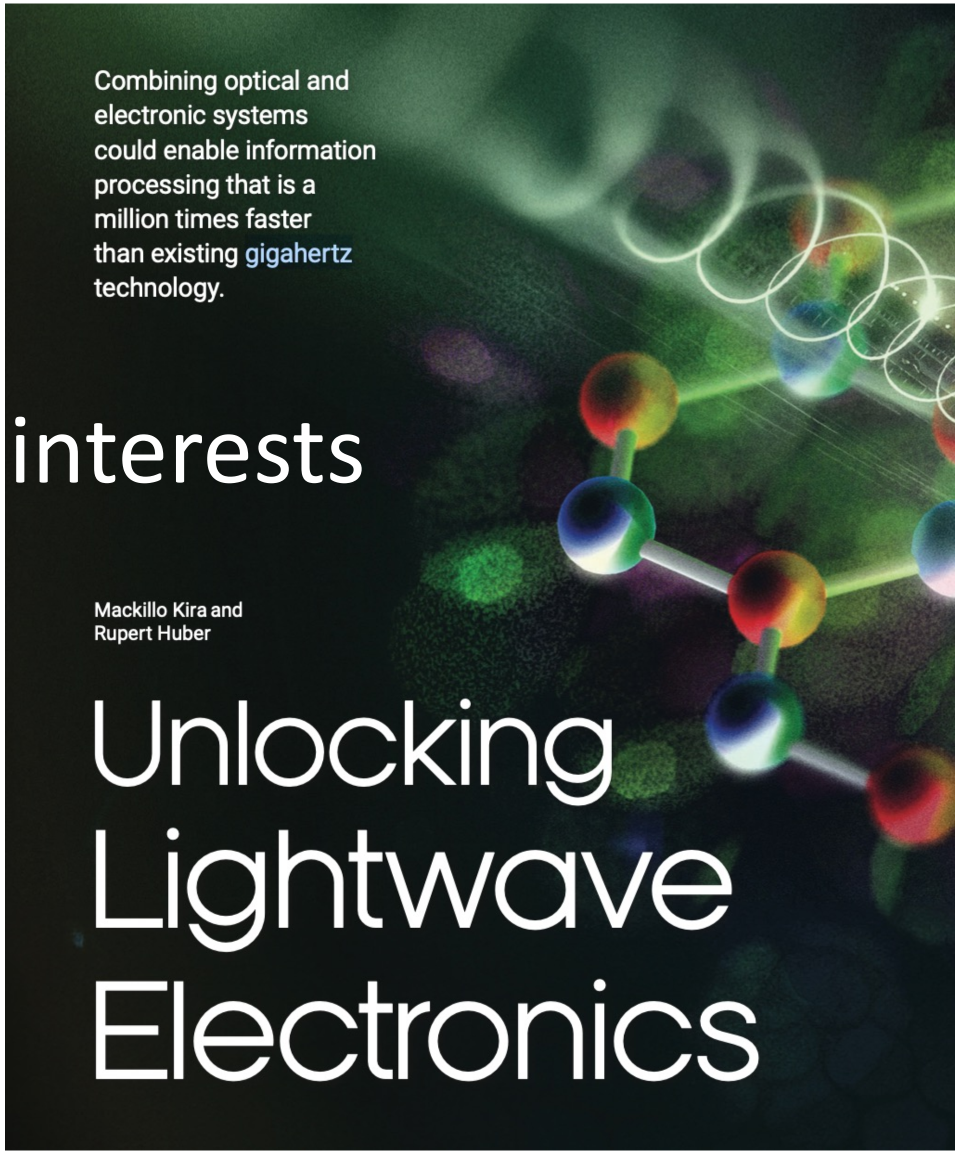
CNT by Nawah



Increasing interests

such as in Optics &Photonics News

(p. 28, Jan, 2025) →



Our Visions on
CNT x Photons

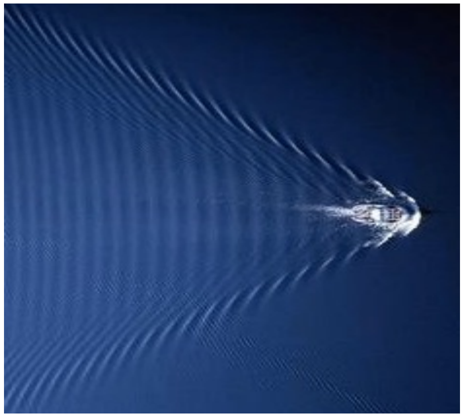
e.g. 1 **CNT**
photons
directly converted
→ **electric current**

e.g.2 **CNT**
→ **electron accelerator**
by **laser**
(LWFA @ ~ n_{cr})

Laser Wakefield (LWFA): photon-driven force in plasma

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 #**



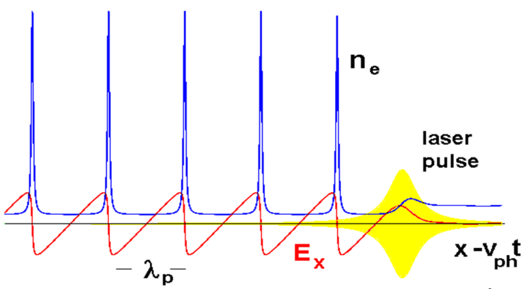
vs

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*)

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

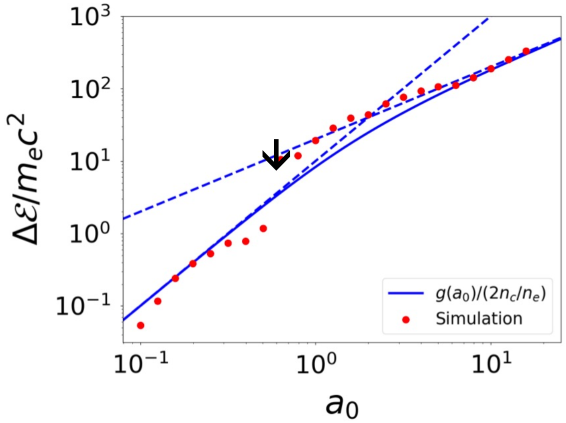
Tajima-Dawson field $E = m\omega_p c/e$ (~ GeV/cm)

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

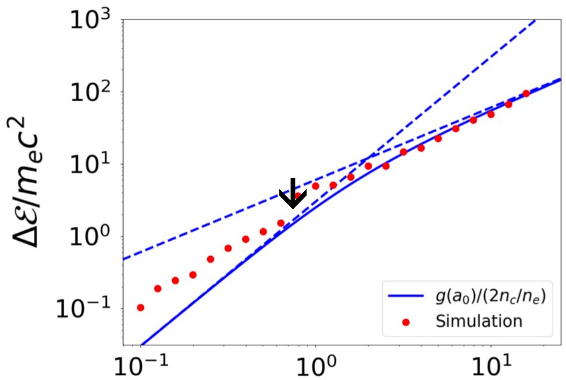
v_{gr} (group velocity of photon) = v_{ph} (phase velocity of plasma wave) << c

(S. Nicks, 2019)

Energy gain

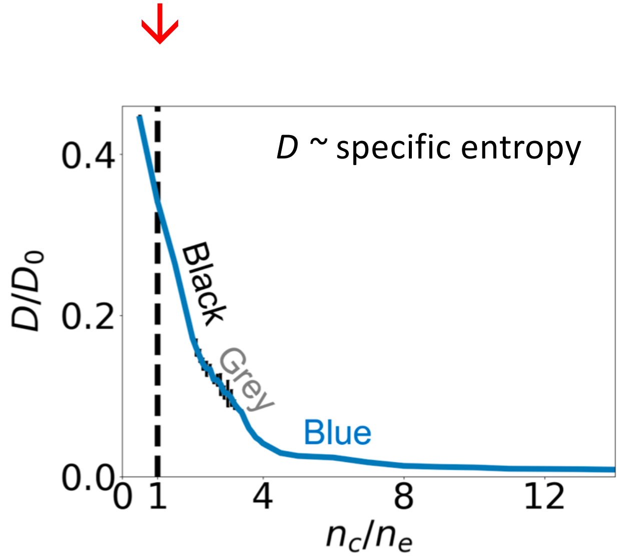


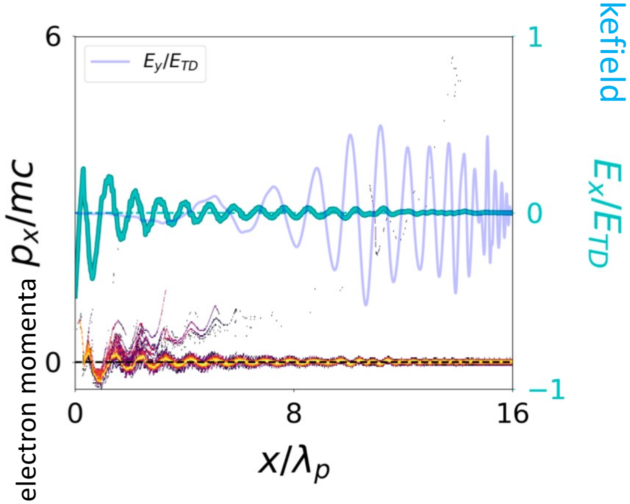
(a) E_{max} vs a_0 for fixed density ratio of 10



n_{cr} / n_e =3

$n_e \sim n_{cr}$





LWFA 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

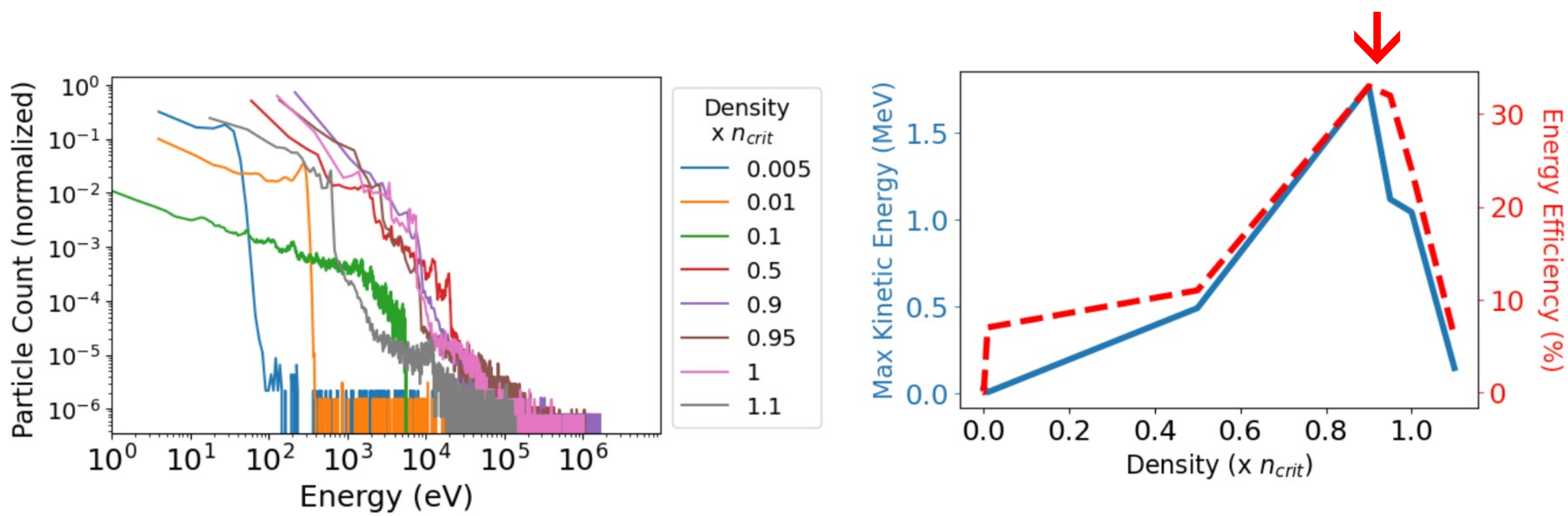
Réagir à cet article

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).

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 $a_0, a_1 = 0.1$, and pulsewidth of 100 fs. The seed laser wavelength was held at λ =1 μm while the pump wavelength was changed in order to satisfy Equation 1. (a) Normalized energy

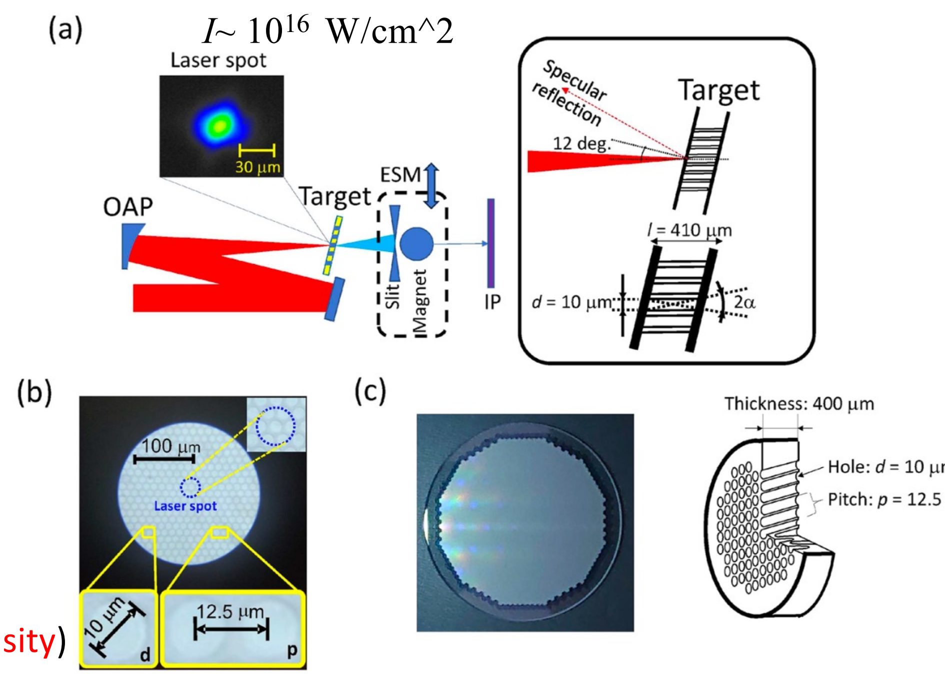
First Experimental Realization of LWFA in nonrelativistic regime in microcavity (2024)

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



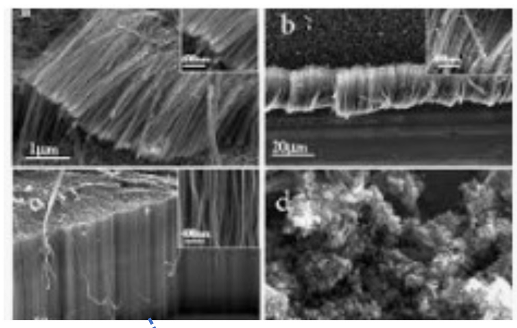
(most efficient acceleration by LWFA happens near critical density)

CNT: compact accelerators (for the future)

Fiber delivery for LWFA at tip of endoscope

Carbon nanotubes on a substrate:

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



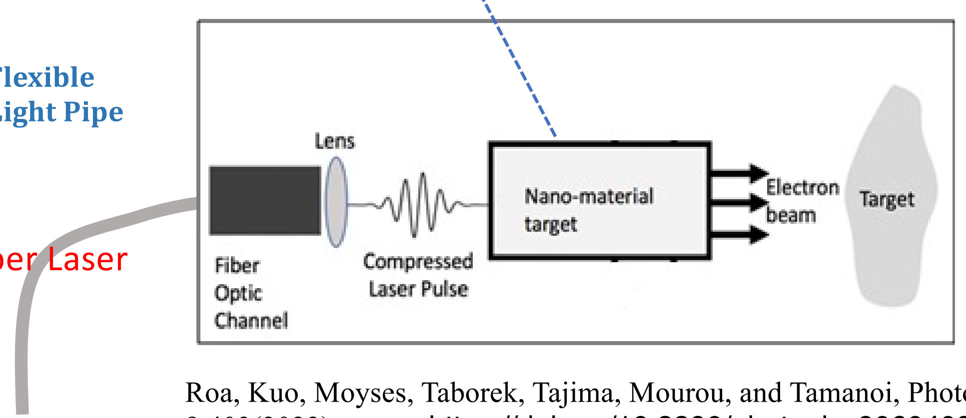
Pick CNT diameter

→ Critical density $10^{21}/cm^3$

(1 μm laser)

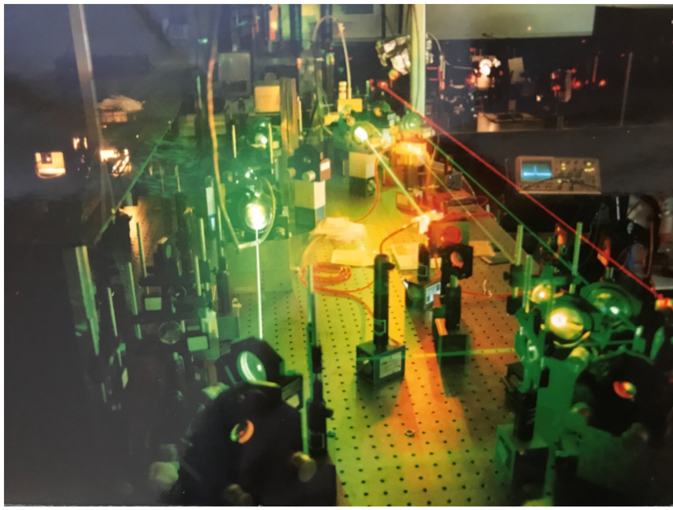
Flexible Light Pipe

Fiber Laser

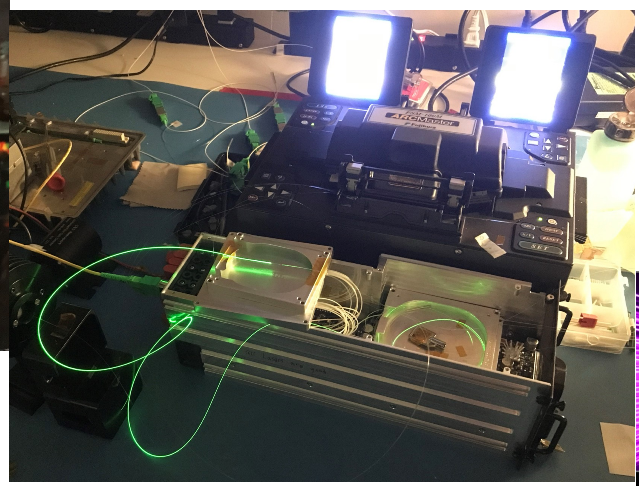


Roa, Kuo, Moyses, Taborek, Tajima, Mourou, and Tamanoi, Photonics **9**,403(2022) https://doi.org/10.3390/photonics9060403

Free-Space Laser vs. Fiber Laser

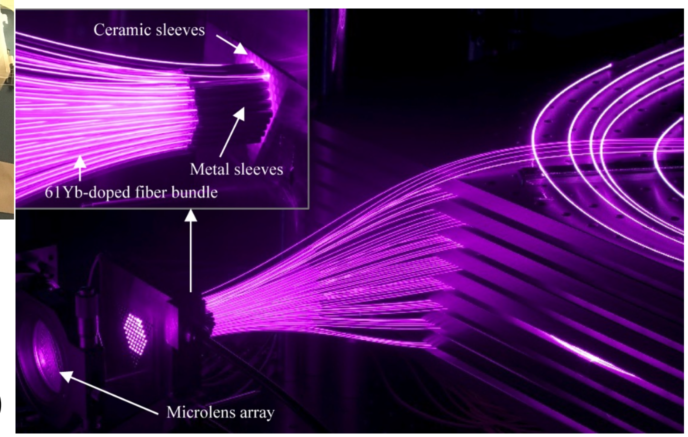


CPA laser
(LWFA stimulated CPA)



Fiber lasers

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



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

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, 2022)

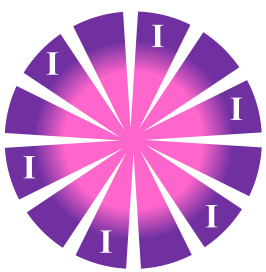
Vector nanomedicine with high-Z metal to target cancer cells for electron radiotherapy

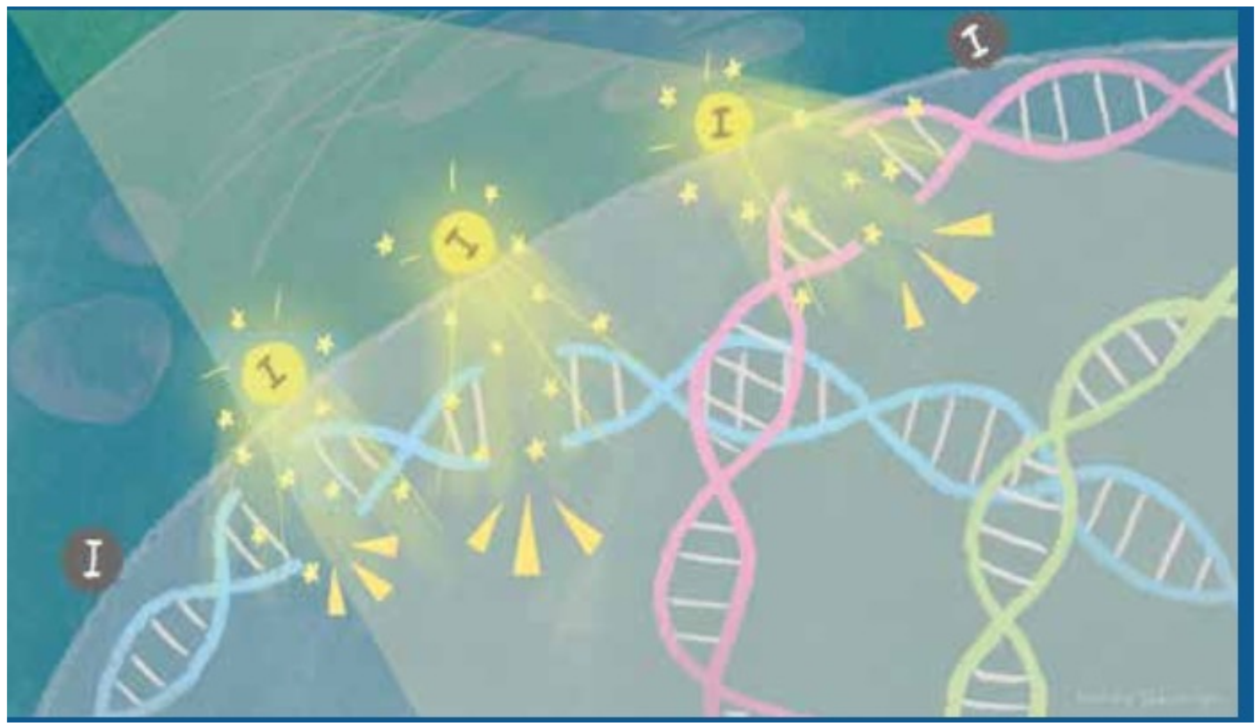
High-Z attached to the vector:

stop **electrons**

Nanoparticle **vector**:

delivered to **cancer cell**





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

Summary of the second part

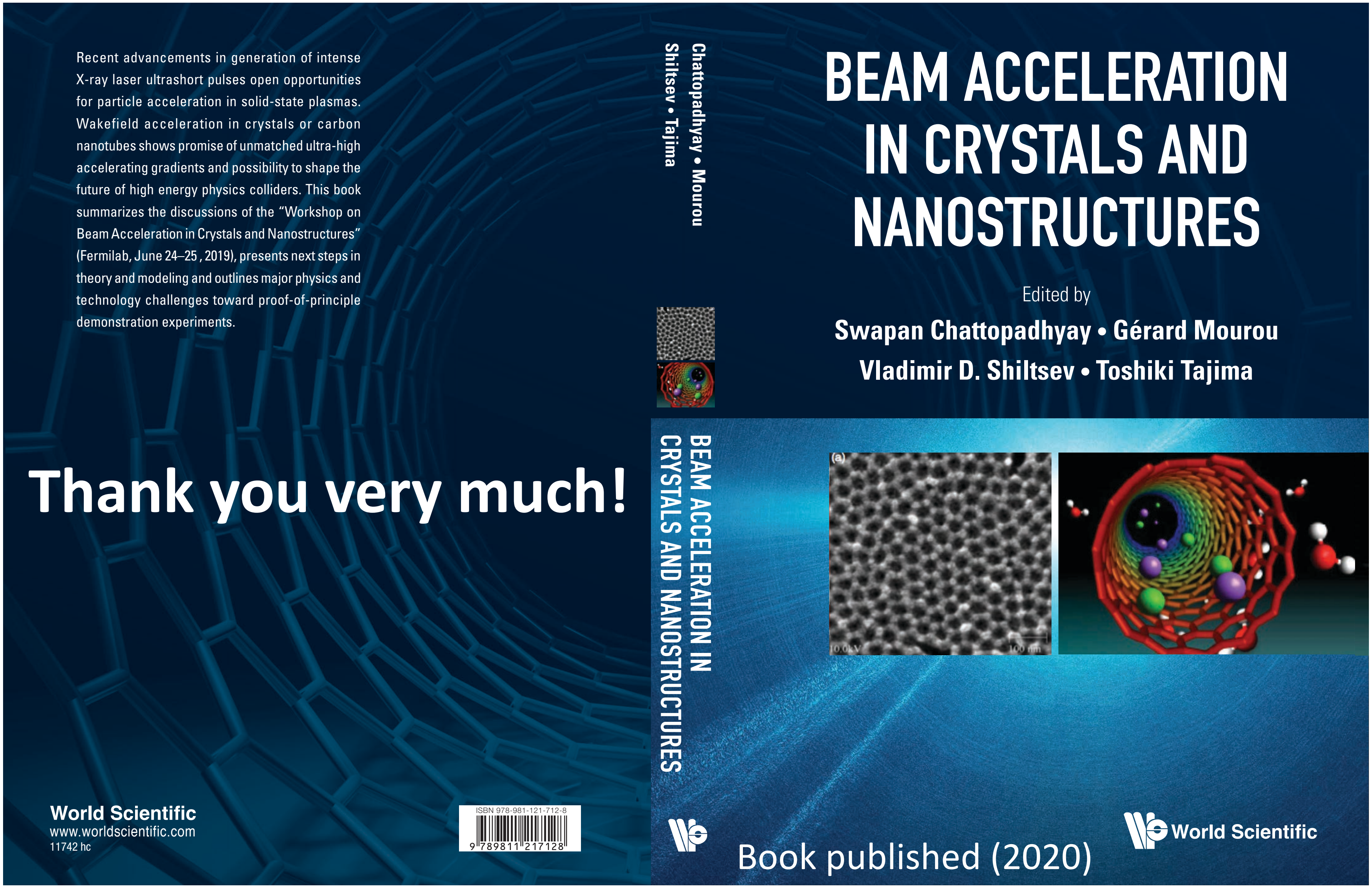
1. Laser wakefield: robust structure and strong compact acceleration

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

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

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

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


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.
Thank you very much!
World Scientific
www.worldscientific.com
11742 hc
ISBN 978-981-121-712-8
9 789811 217128
Chattopadhyay • Mourou
Shiltsev • Tajima
BEAM ACCELERATION IN CRYSTALS AND NANOSTRUCTURES
BEAM ACCELERATION IN CRYSTALS AND NANOSTRUCTURES
Edited by
Swapan Chattopadhyay • Gérard Mourou
Vladimir D. Shiltsev • Toshiki Tajima
(a)
World Scientific
Book published (2020)


Thank you