NanoAc Workshop 2025 (Cockcroft Institute / Univ. Liverpool , Nov. 6, 2025)

Laser Wakefield Electron Sources for Endoscopy

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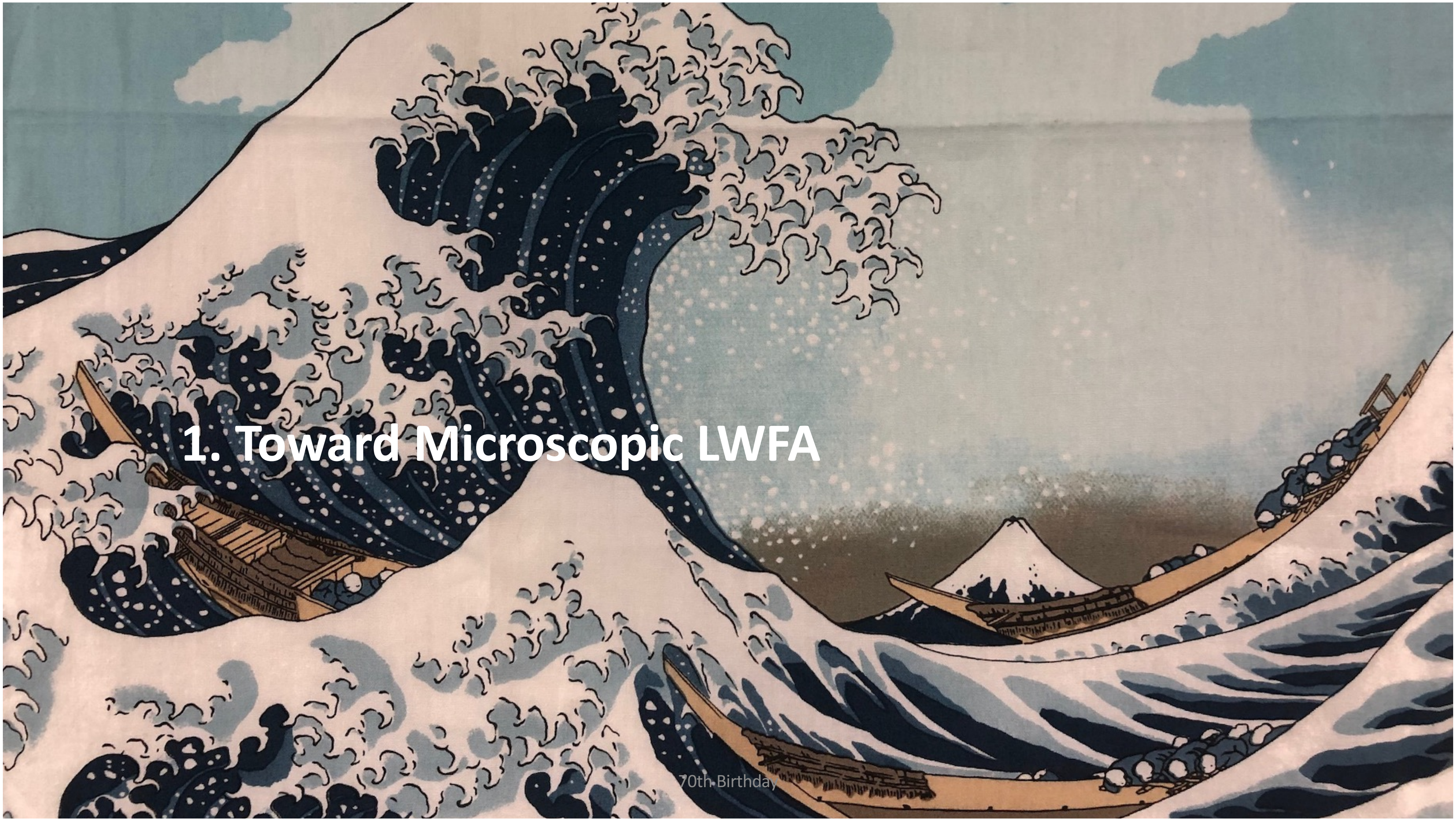
C. Welsch, W. J. Sha, J. Kuo, D. Roa, G. Mourou, D. Strickland, S. Iijima, V. Klumper, Q. Dang, E. Barraza, G. Koumarianou, H. Lee, J. C. Chanteloup, F. Tamanoi, P. Boulanger, V. Shiltsev, T. Kawachi, M. Mori, F. Krausz, T. Massard



1. Toward Microscopic LWFA

Wake

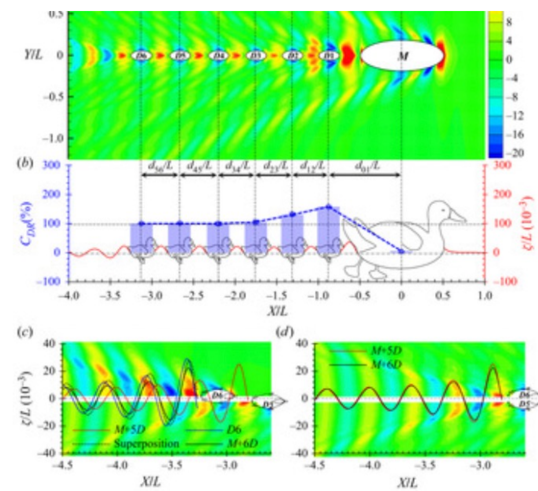
Wake by a duck on a lake:

Nature (or mother duck) shows us

Wake by a **laser** pulse

extremely compact (micrometers μm), extremely intense **acceleration**

(1979, Tajima and Dawson)

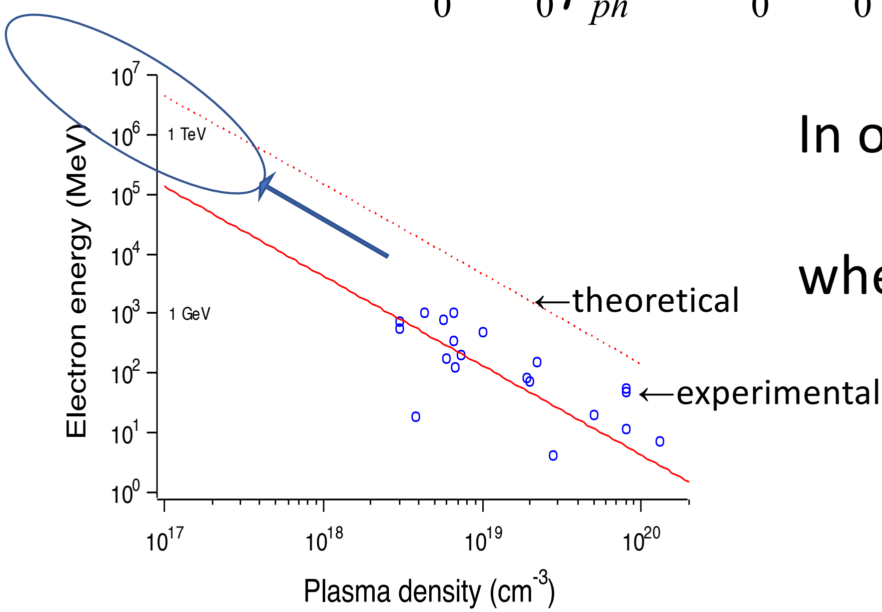


Yuan et al. JFM (2021)

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)
→ 10^{29} (10keV photon)
n_e = 10^{16} (gas) → 10^{21} /cc(porous solid)

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

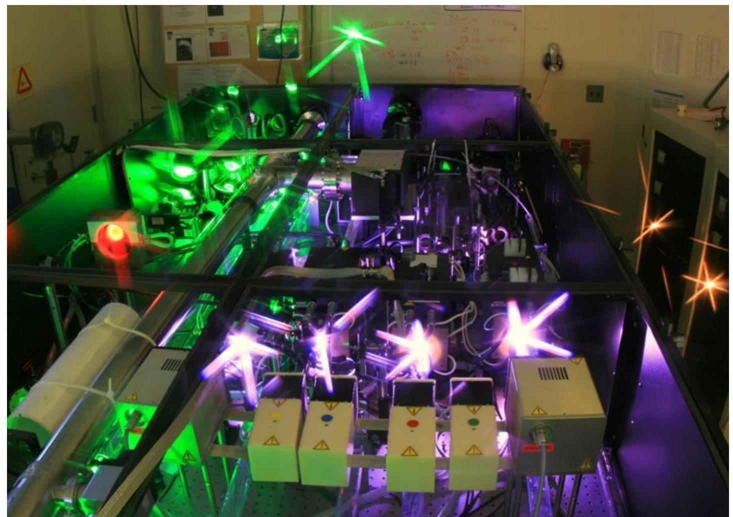
dephasing length

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

pump depletion length

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

(2004)



(Michigan)

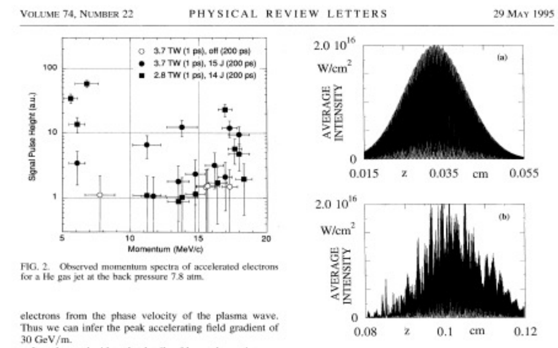

VOLUME 74, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 1995

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

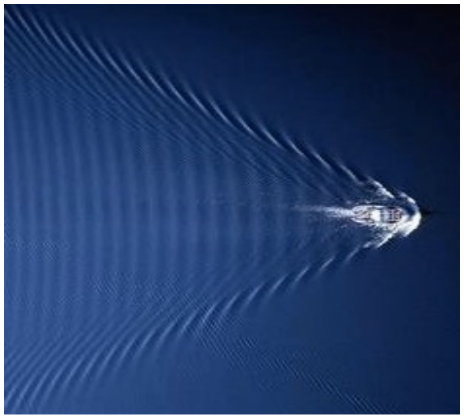
←

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 #**



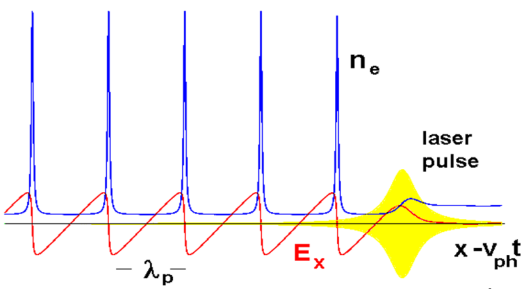
vs

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)

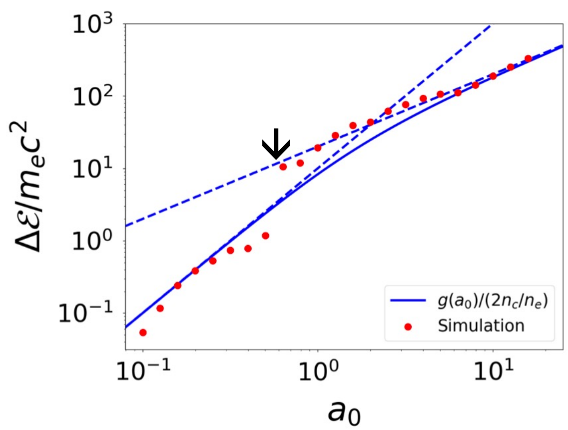
Tajima-Dawson field $E = m\omega_p c /e$ (~ GeV/cm)

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

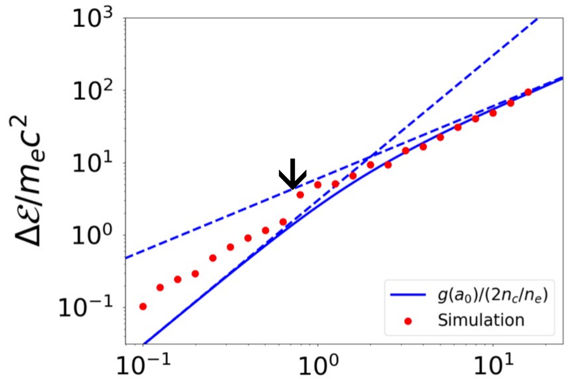
v_g (group velocity of photon) = v_p (phase velocity of plasma wave) $\ll c$

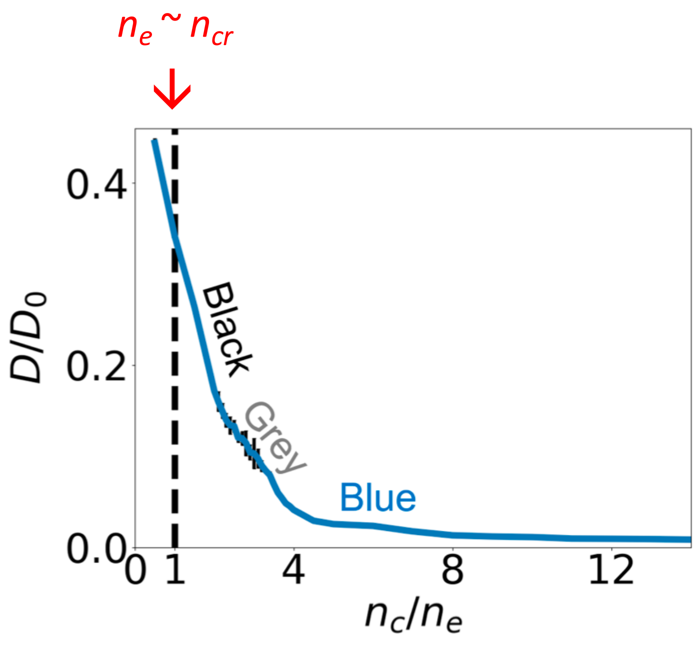
v_{tr} = sqrt (eE / mk) (trapping width), self-injection easy

Energy gain

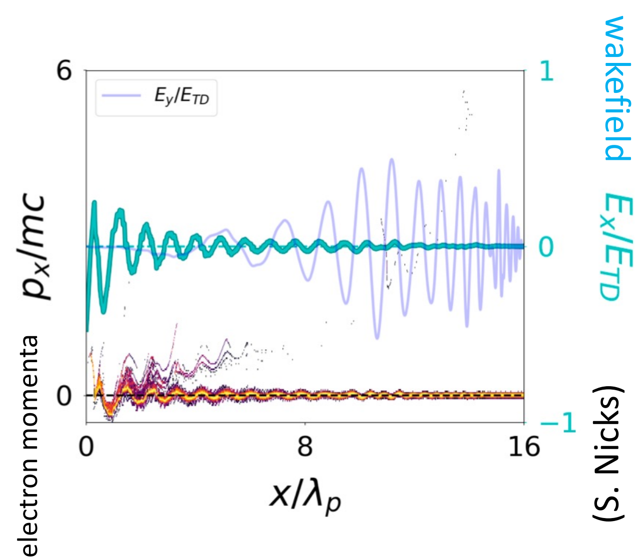


(a) E_{max} vs a_0 for fixed density ratio of 10





D ~ specific entropy / efficiency of coupling



2. CNT targets at near critical operation

First Experimental Realization of near-critical density LWFA in microcavity (2024)

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

Experimental realization of near-critical-density laser wakefield acceleration: Efficient pointing 100-keV-class electron beam generation by microcapillary targets

Cite as: AIP Advances 14, 035153 (2024); doi: 10.1063/5.0180773
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View Online Export Citation

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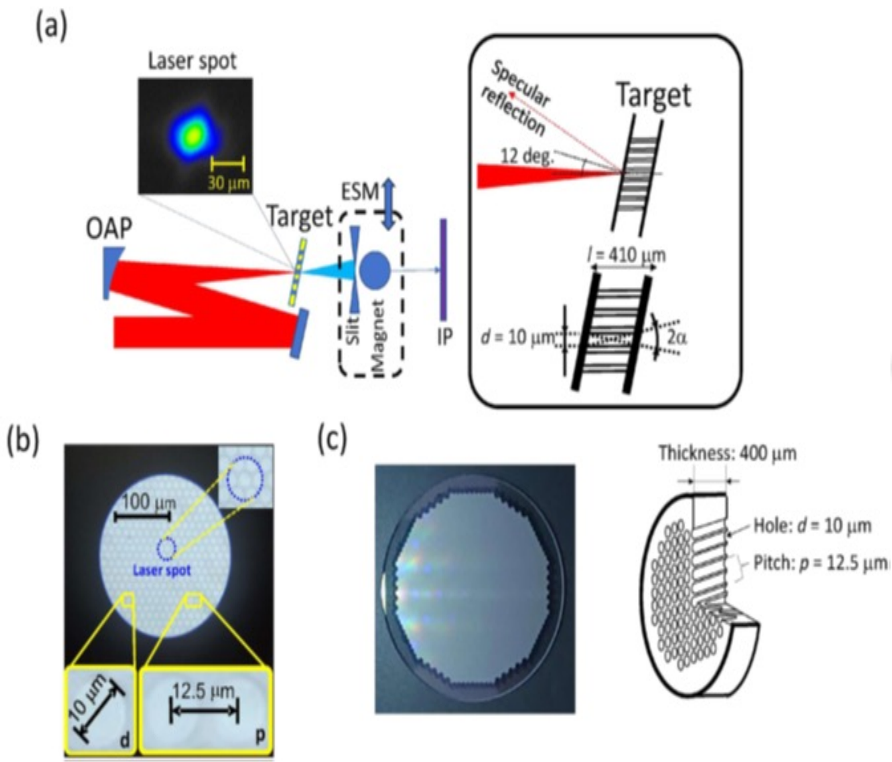
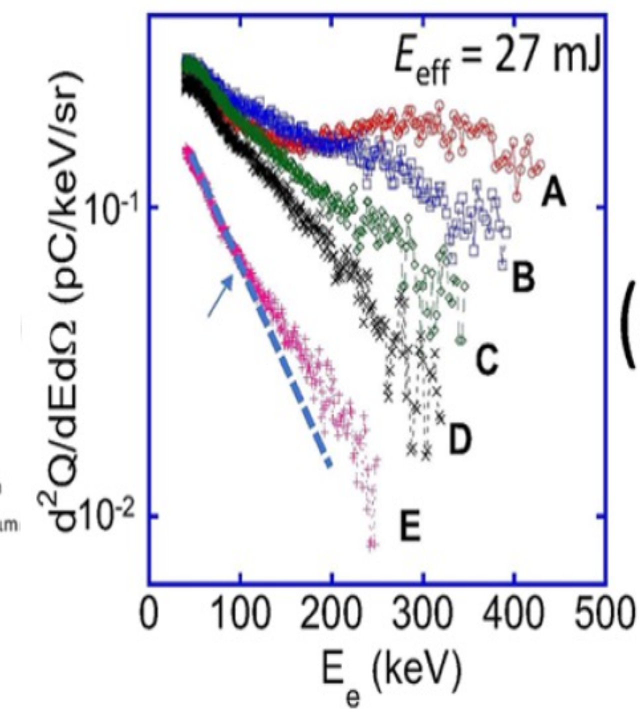
(most efficient acceleration by LWFA happens near critical density)

Microcavity: strong electron pickup at near critical density in micronic target



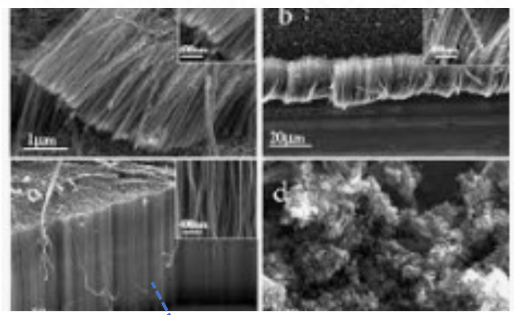


$I \sim 10^{16}$ W/cm^2

CNT: compact accelerators (for the future)

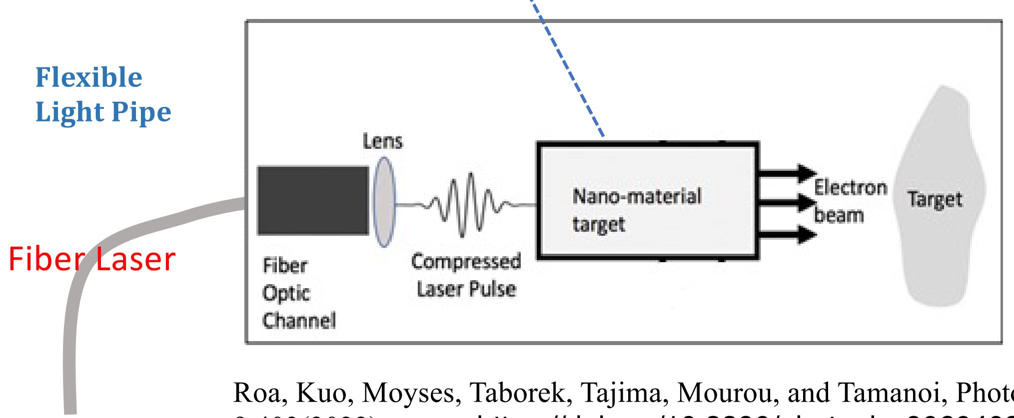
Fiber delivery for LWFA at tip of endoscope

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)

(Quynh and Greta are working toward CNT)



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

Carbon nanotube (CNT) discovery (1991)

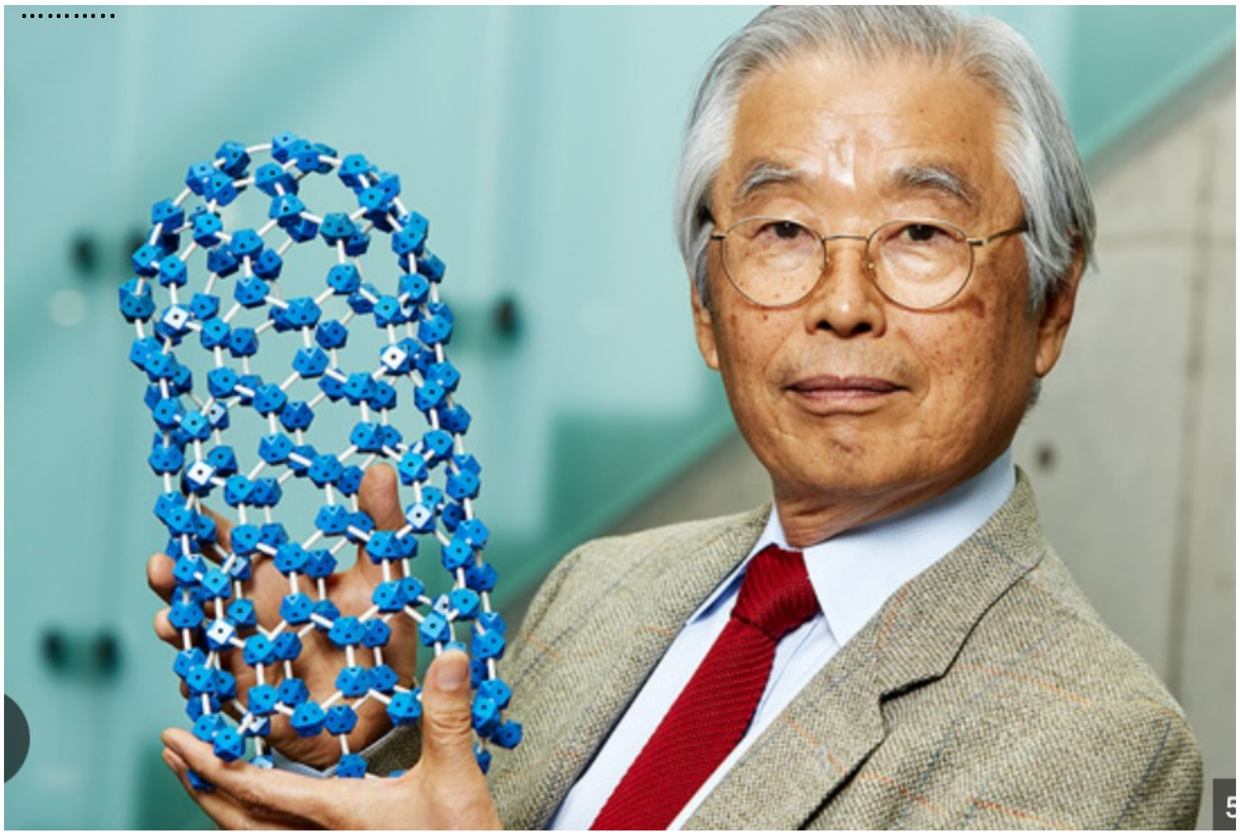
Prof. S. Iijima： then NJ NEC, Nature (1991)， discovered **CNT** out of smoke dusts

T. Tajima (UT Austin, Inst. Fusion Studies (IFS); invited Iijima to his workshop (1992)。

H e was invited to give his seminar at UCI (2025)

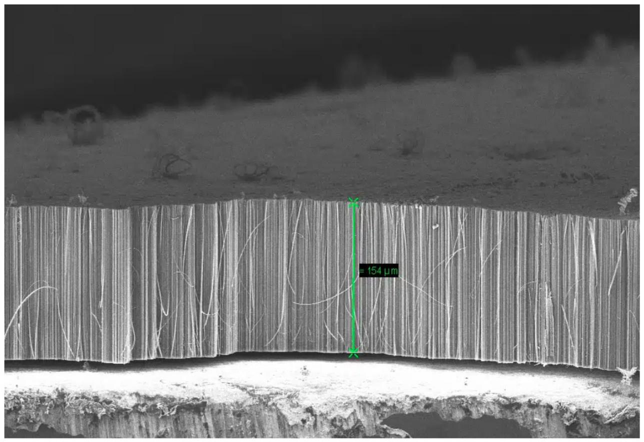
[**Graphene** discovered (2004).]

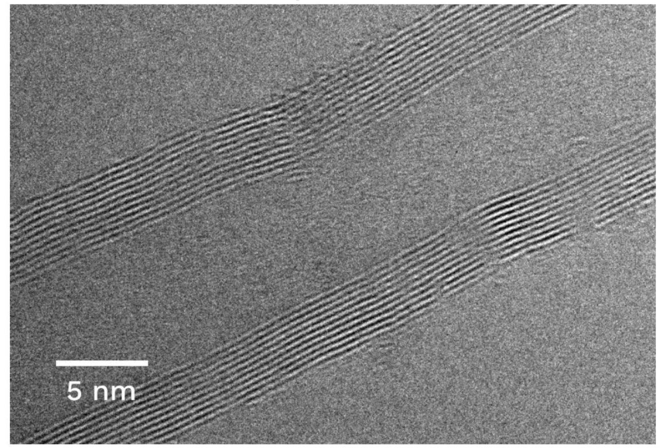
………..

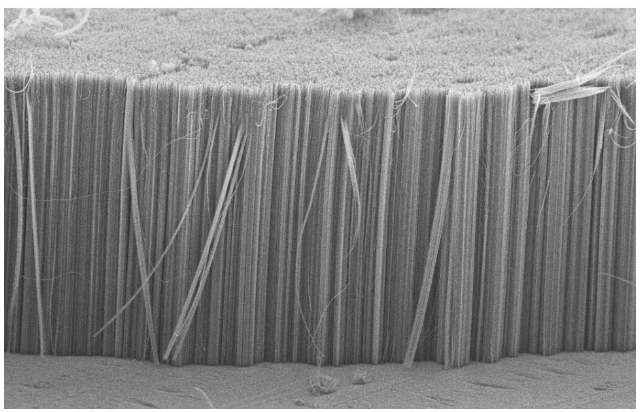


Carbon nanotubes on a substrate (nm scales):

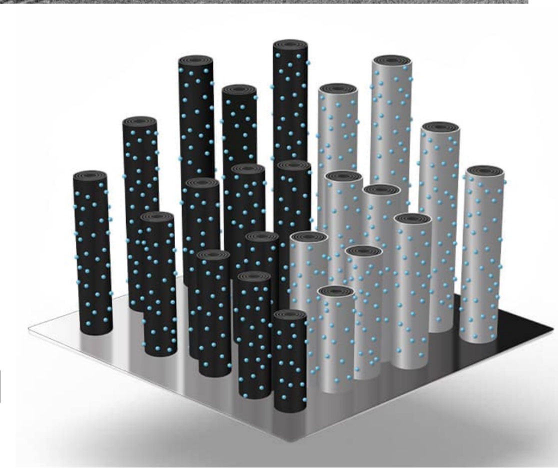
→ toward **Carbon Nanoforest** **(no need for plasma w/vacuum)**







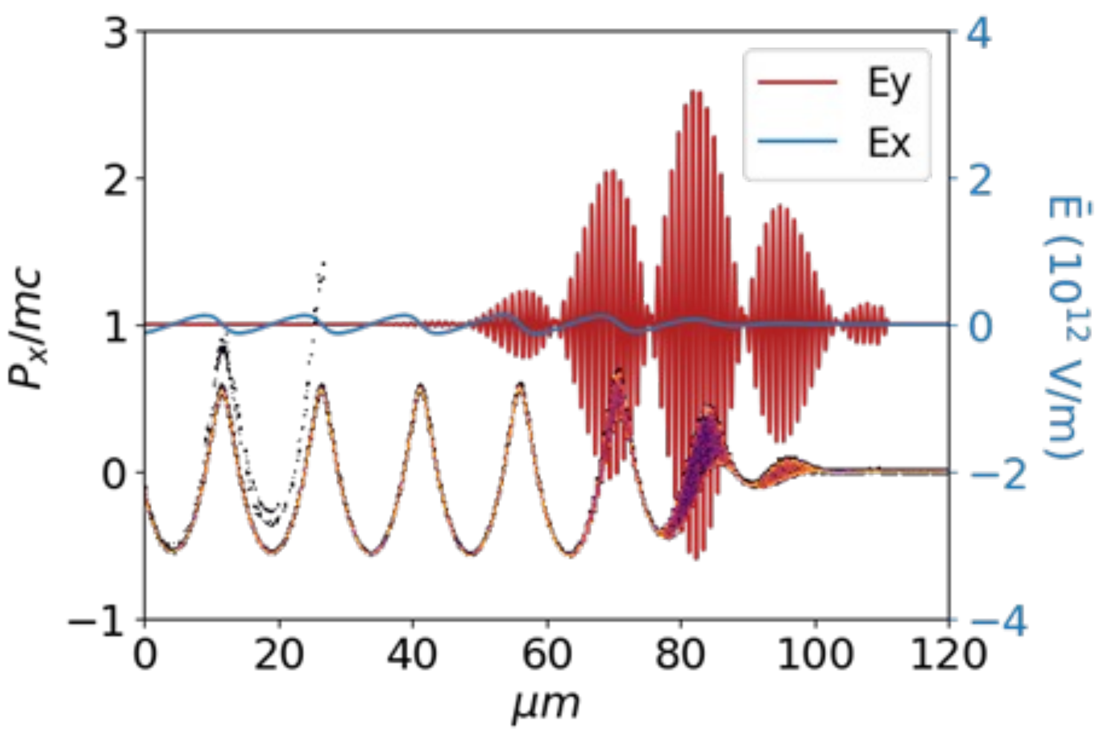
NAWAH



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

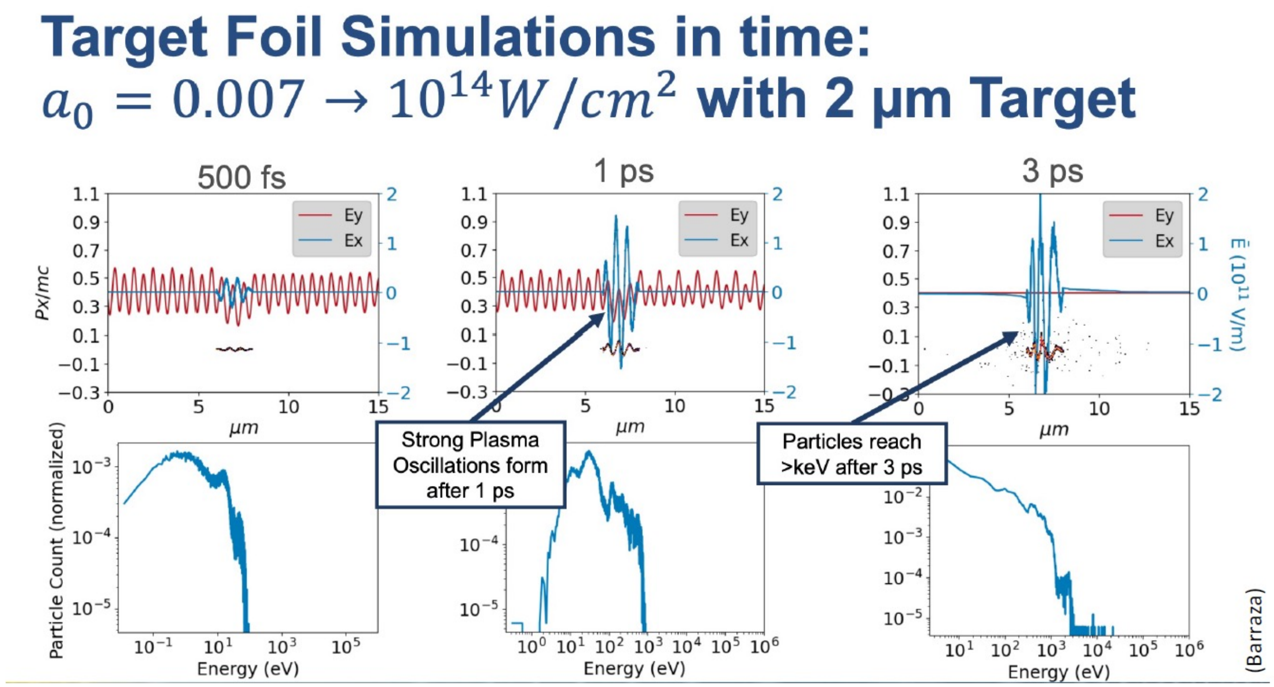
$$v_{ph} = \frac{\omega_p}{k_p} = \frac{\omega_0 - \omega_1}{k_0 - k_1} \qquad v_g = \frac{\partial \omega}{\partial k} = c\sqrt{1 - n_e/n_c}$$

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])

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

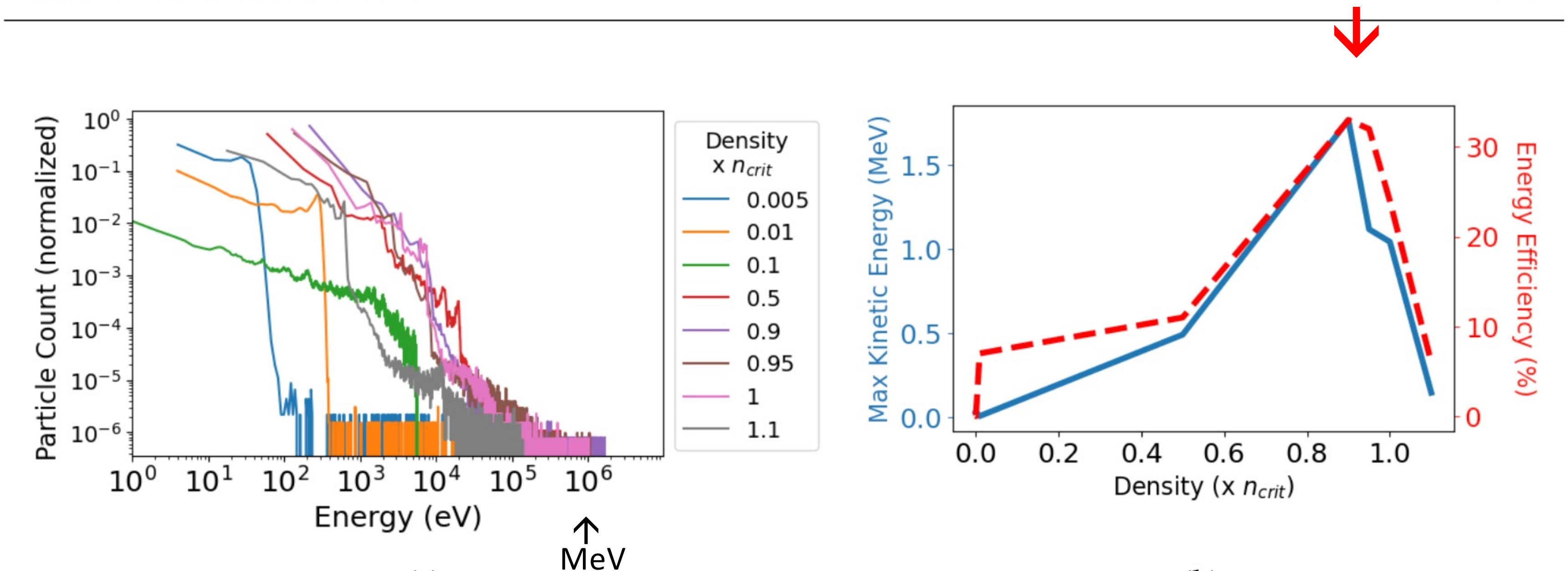
Beat-wave laser acceleration of electrons on thin target



Laser parameter, wakefield magnitude, electron momentum and energy from beat-wave LWFA simulations for endoscopic accelerator. Studies are given in reference [7]. This plot is from private communication with E. Barraza.

Simulation study: low intensity laser near critical density

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

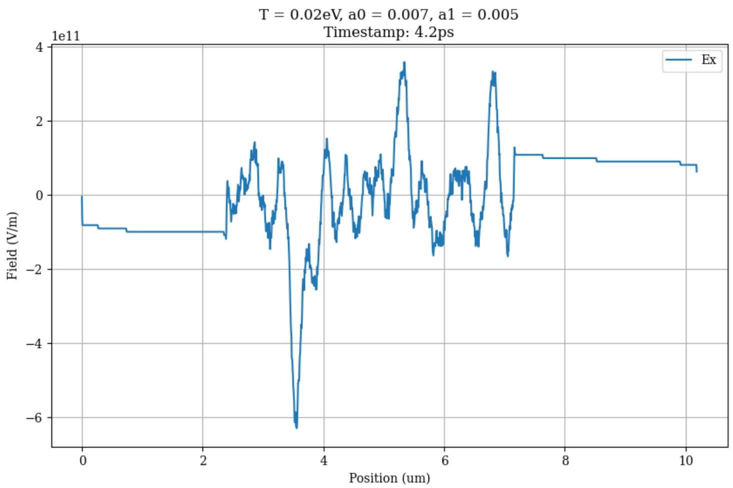


(a) **(b)**

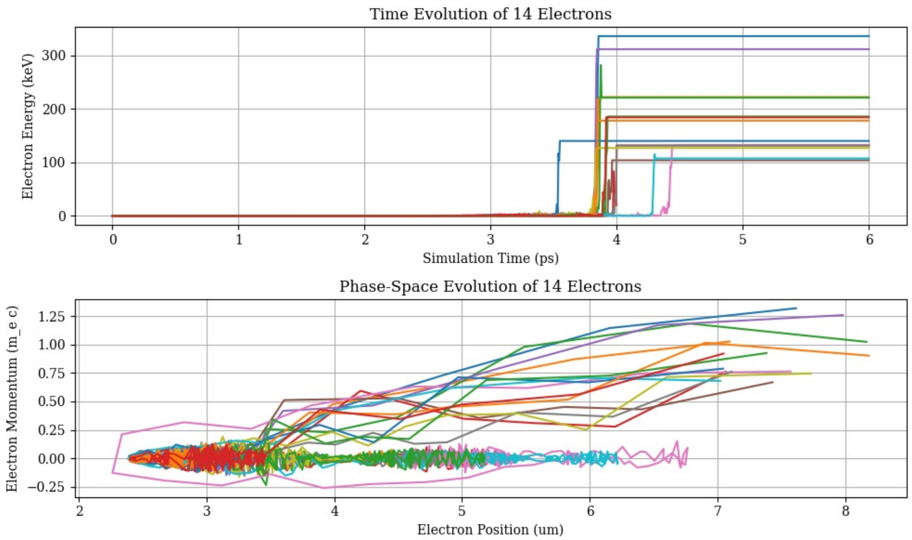
Figure 3. Energy distributions, maximum kinetic energies, and laser to total particle energy efficiency with respect to plasma density for BWA simulations after 1 ps using gaussian lasers with intensities of a, a = 0.1, and pulsewidth of 100 fs. The seed laser wavelength was held at λ =1 μm

Electron Energy Gain: Thin CNT irradiated by Beat Wave

Beat wave excitation



Electron energy gain inside the thin CNT

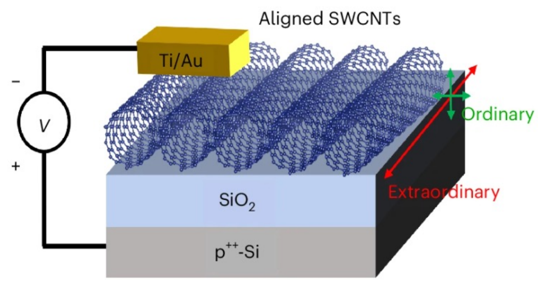


(CNT starts at 2.2micron and ends at 7.3micron
Energy gain: up to ~300keV)

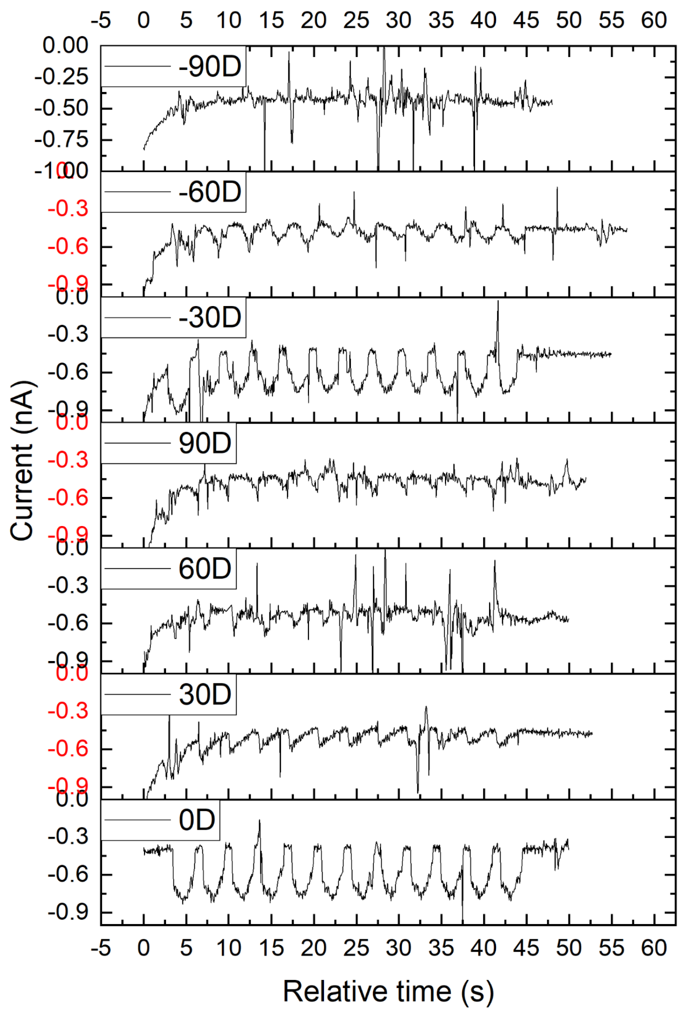
(Klumper)

CNT immersed in nitrogen gas (experiments): Irradiated by Laser

Current response (-10V)



- Laser exposes periodically
- exposure time ~ 3.1s
- Stronger response at certain polarization
- Neg V → higher E_{Fermi} → electron injection (electrons filling the holes)
- Minimal doping (n-type) + most charges confined at interface (Debye length) → modulate overall optical properties effectively
- In contrast, in heavily-doped film, the free carrier screens, rearrange, and cancel out applied E-field



(Q. Dang: experiment)

3. Fiber laser technology and access endoscopically

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

↓

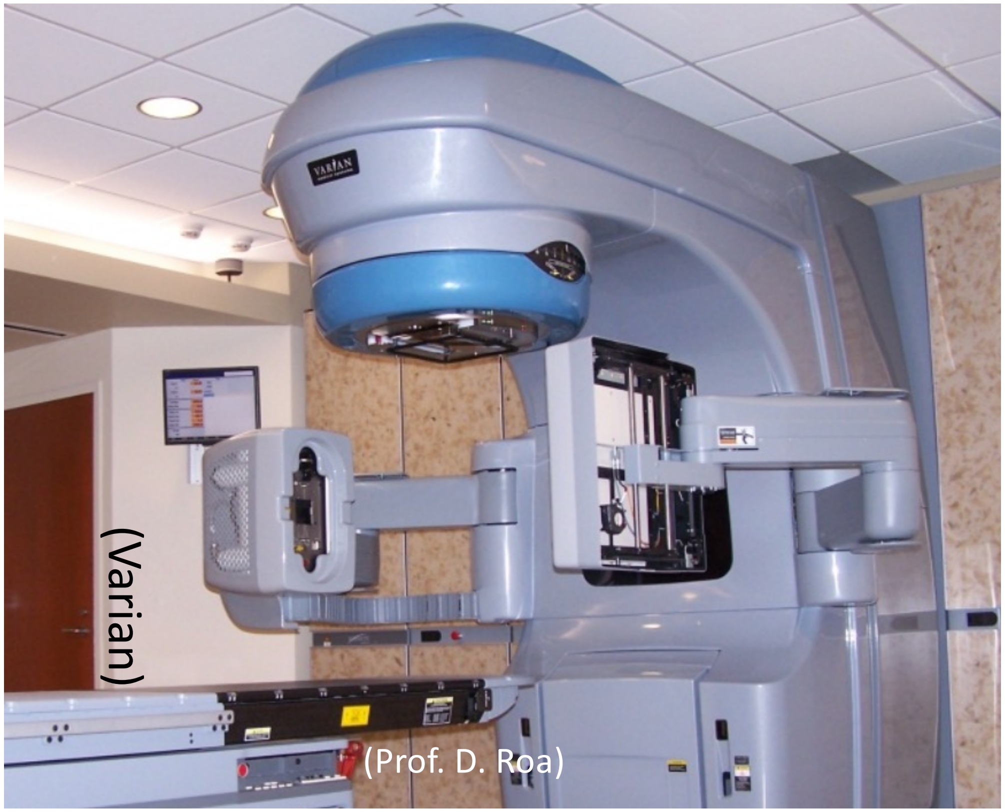
Furthermore, much tinier with **fiber**

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

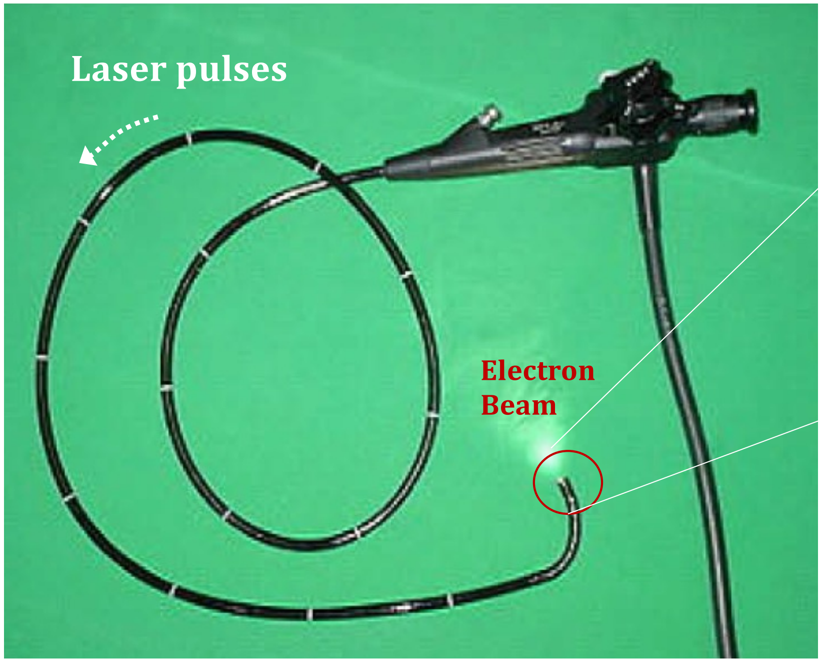
^ Body penetration

↑ Cancer cell size
Capillary size

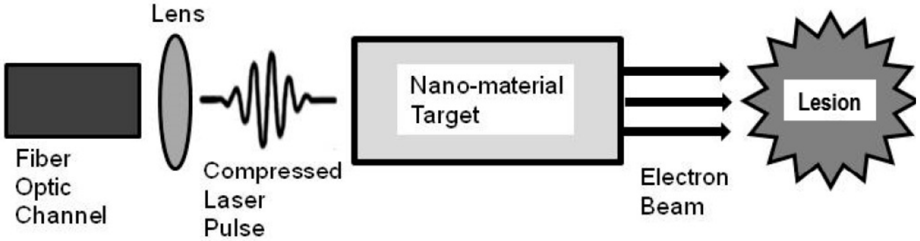
← 5-10m (next room) →



Endoscopic Accelerator for Targeted Cancer Therapy



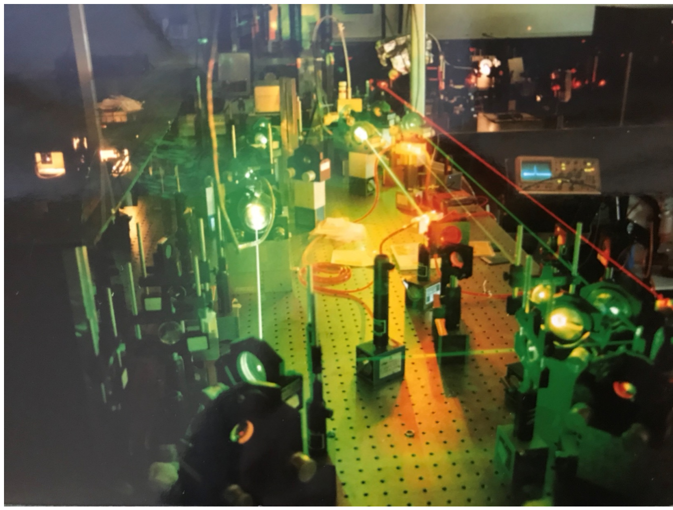
Micron-scale laser electron accelerator
Electron beam 10 – 100 keV



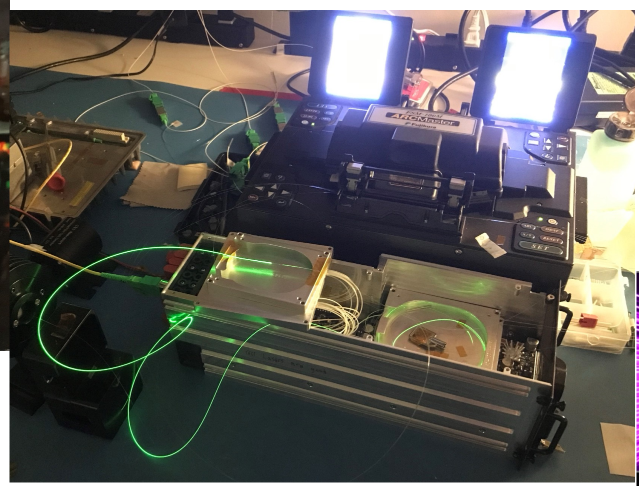
Near-critical density regime laser plasma acceleration
10^{14} to $10^{15} W/cm^2$, Gigawatt compact laser

Roa, Kuo, Moyses, Taborek, Tajima, Mourou, and Tamanoi, Photonics (2022)

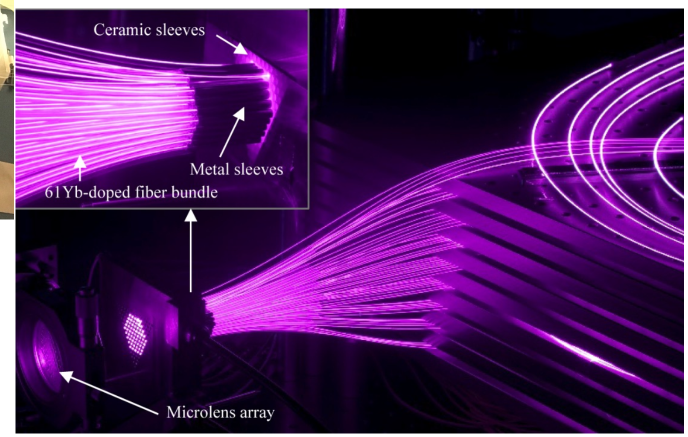
Free-Space Laser vs. Fiber Laser



CPA laser (Nobel: Mourou, Strickland)
(LWFA stimulated CPA)

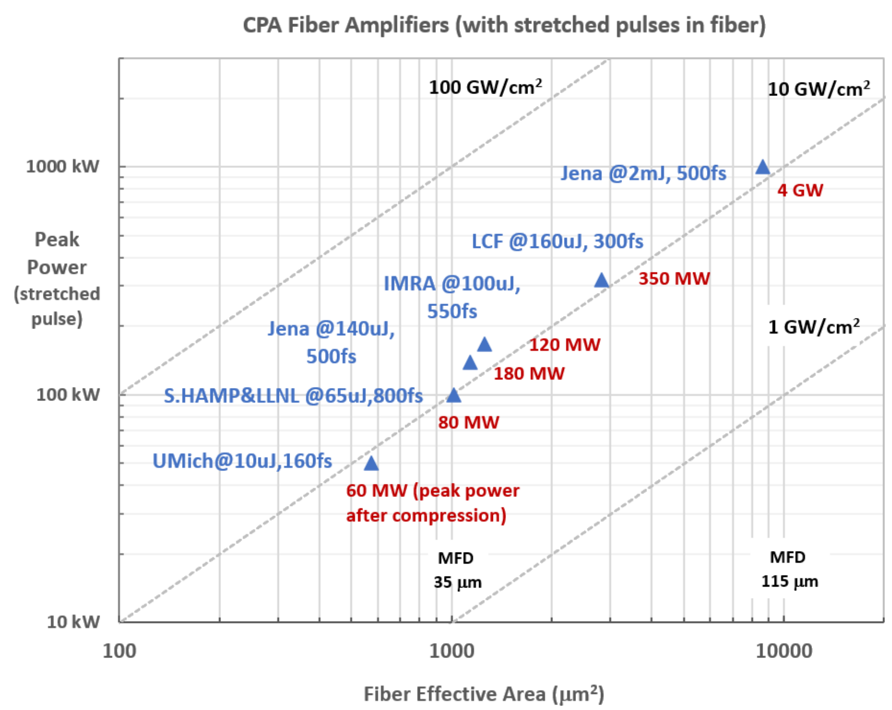


Fiber lasers



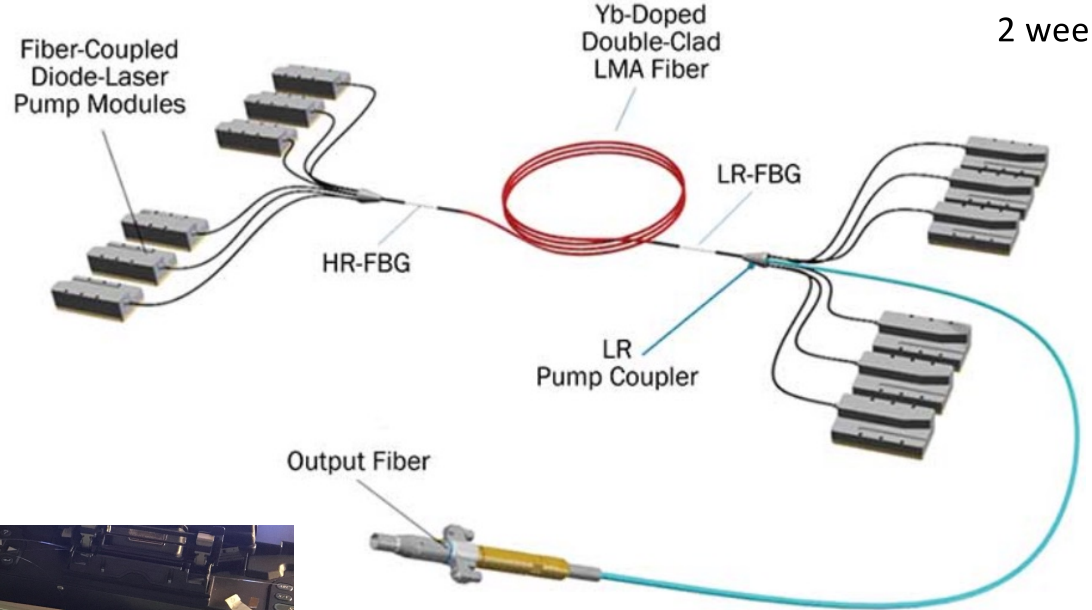
(CAN fiber laser;
Prof. Chanteloup, Aug. 5, 2024)

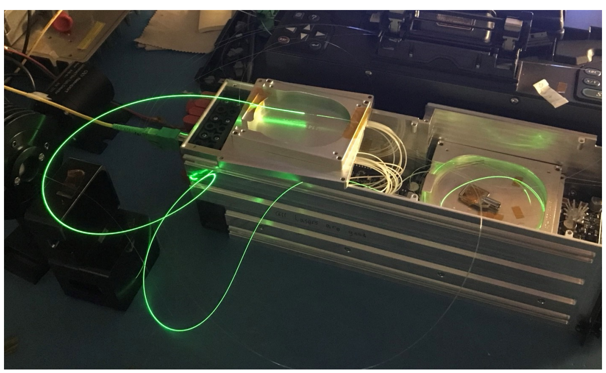
Fiber **diameter** and the fiber laser intensity



Fiber Laser Construction, Example

W. Sha, who spoke
2 weeks ago (2025)





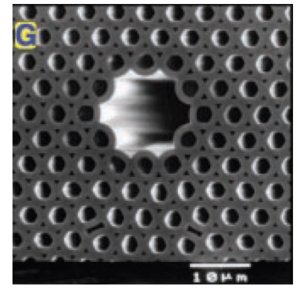
Hollow-core fiber for light pulse delivery

W. Sha (2025)

"Photonic bandgap guiding" instead of TIR(total internal reflection)

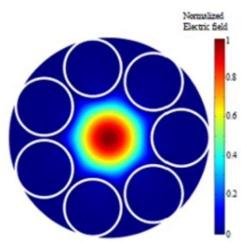
Anti-resonant in cladding, light guiding in hollow core: **damage** ↓↓, **nonlinearity** ↓↓↓

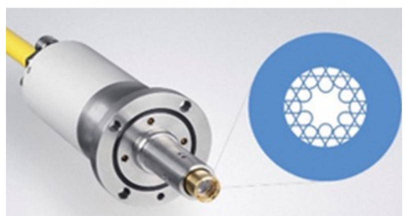
→ Higher intensity

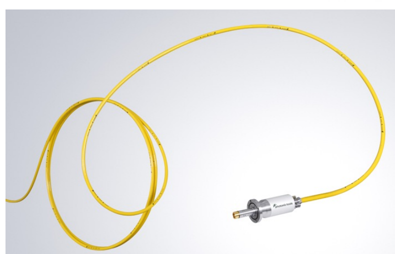


P. Russell, *Science* 2003

PT photonics product catalog

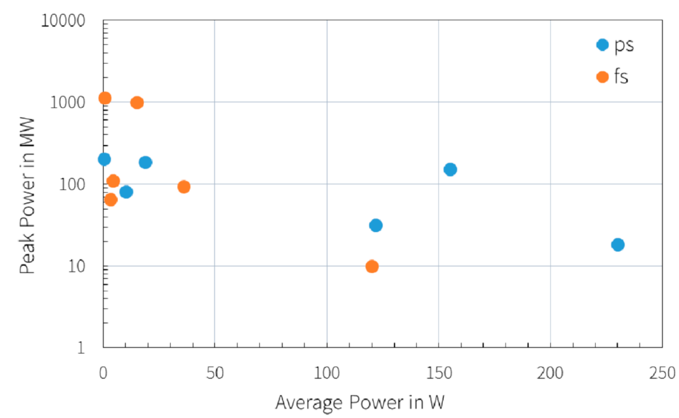






Bending radius 25 cm

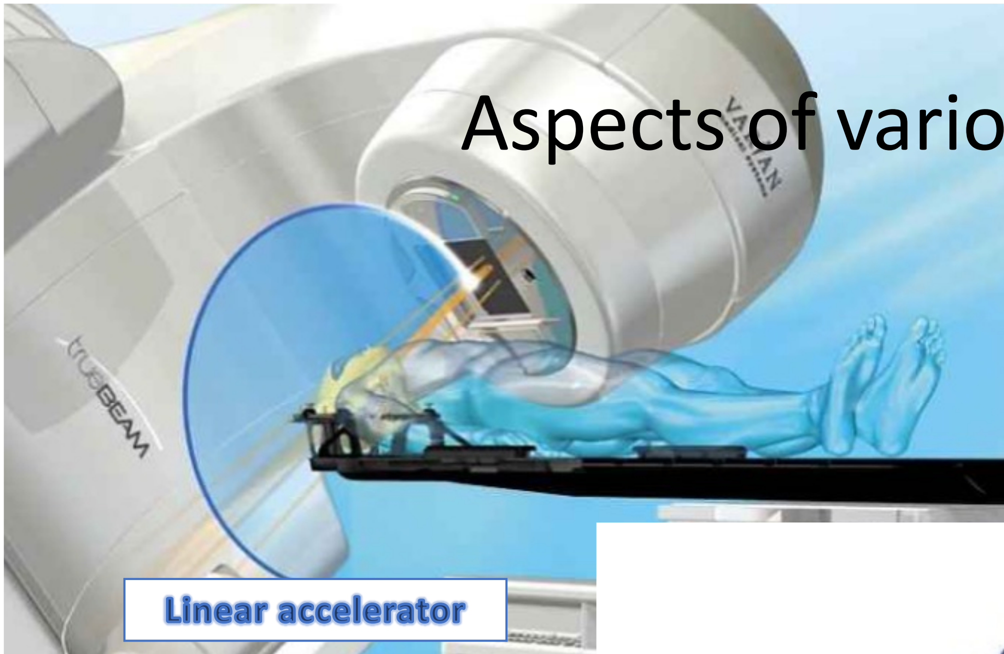
Hollow-core delivery up to GW peak power



Eilzeret al., MDPI *Fibers*, 2018

4. Endoscope with CNT and laser: cancer and cardiological therapies

Aspects of various therapies



(Kuo)

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 opérationn 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

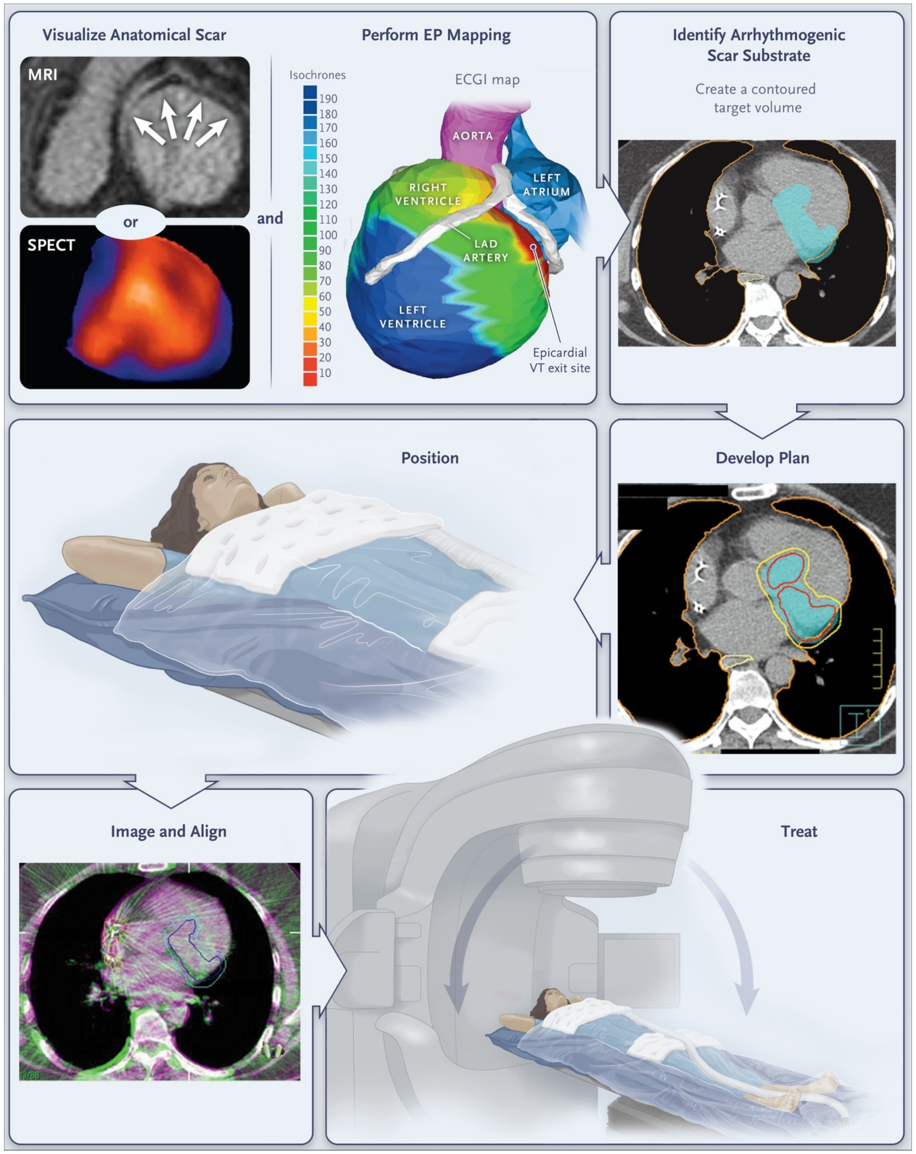
La SFRO élit un nouveau bureau pour les deux prochaines années
14/02/2024 : Le nouveau Bureau de la Société Française de Radiothérapie Onologique vient d'élire sa nouvelle en la personne du Pr Véronique Vendrely. Il s'inscrira dans la continuité des actions de l'équipe précédente et es de trois collèges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

(Beyond Cancer)

→ Cardiac pathway

s.a.
ventricular tachycardia

Extra cardiac
tissue
ablation



Curulich, et al.
N.Engl. J. Med.
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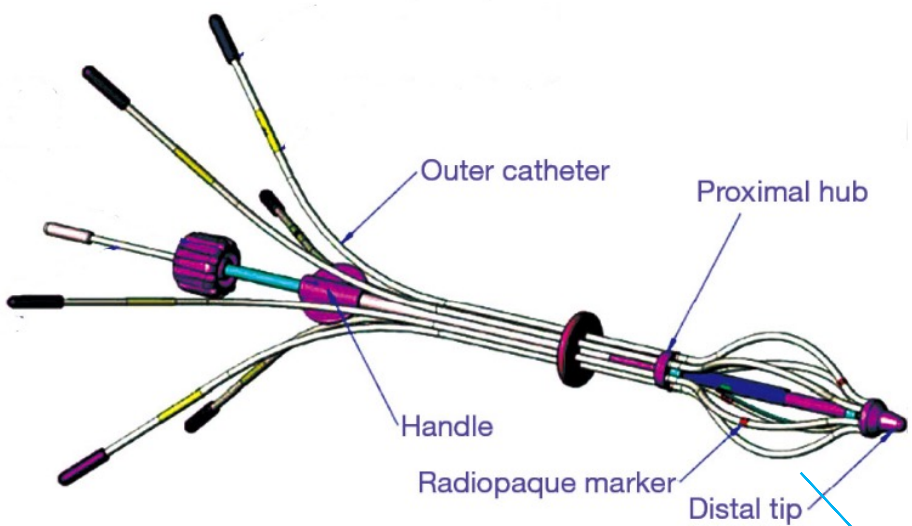
(Kuo)

Hypothetical LWFA cardiac ablation devices



Volumetric radioablation (i.e. a-fib)

Point radioablation (i.e. V-tach)

LWFA channel source(s)
EPS sensors
Ion chambers

What Can You Do With a Novel Radiation Source?

	Replace existing radiation technology	Replace other technology	New applications
Indications	Same	Same or new	New
Toxicities	Less	Same or less	TBD
Cost	Same or less	Same or less	TBD
Example(s)	▪ Radionuclide brachytherapy ▪ IOERT ▪ Superficial electron therapy	▪ Cardiac arrythmia ablation ▪ Radiofrequency ablation	▪ TBD

cf. Cost **estimate** comparison in the case of radiotherapy

↓

	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. Dante Roa, preliminary estimate, 2022)

Summary

1. Laser wakefield: robust structure and strong compact acceleration:
   particularly compact and <u>robust at near critical density</u>

2. <u>Using fiber laser</u> and carbon nanotube targets →
   no vacuum necessary
   small (< mm) electron sources (~100keV)

3. <u>Endoscopic</u> (through fiber) delivery of electrons for cancer and cardiology
   becomes possible

3. Research: just started